Advancing Quantum State Preparation algorithms: from the variational SRBB-based ansatz to its exact version

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Abstract: Novel QSP algorithms have been designed by synthesizing traditional UCGs with (i) a variational ansatz structured on Lie algebras, (ii) an exact procedure, and (iii) ancillary qubits. Their algebraic structure guarantees modularity and further optimizations.

Quantum State Preparation (QSP) has become an increasingly transversal procedure, which is employed as a necessary primitive in many quantum algorithms. The efforts to reduce its circuit complexity and extend its application are still a significant challenge. Variational approaches allow for low-depth circuit ansatz at the cost of non-convex optimization landscapes that severely limit scalability. In contrast, exact methods typically involve exponential growth in the number of parameters, leading to depths prohibitive for current NISQ hardware. Over the past year, trying to overcome this delicate trade-off, four algorithms have been proposed sequentially.

First, the traditional QSP architecture composed by increasing layers of uniformly controlled gates (UCGs) is rephrased in a variational perspective [1]. Each layer of UCG has been implemented by means of the CNOT-optimized diagonal component of the Standard Recursive Block Basis (SRBB) [2]. Depth and gate count come both from the SRBB decomposition and the modularity of this framework, called VQSP-SRBB, which defines the variational circuit of a new quantum neural network (QNN) where the real part of the target state is learned separately from the complex one. Test have been conducted in simulation and on real hardware (Fig. 1, left and center). With the aim of a meaningful comparison with the literature, the theoretical and exact QSP algorithm with asymptotically optimal space-time trade-off bounds [3] has been implemented using ancillary registers [4] and further optimized [5]. Preparing the real part separately from the complex one leads to reduce depth and gate counts: the new algorithm called OSUN uses only one lambda operator instead of the 3 theoretically proposed by the literature for each UCG level (Fig. 1, right). Finally, the UCG-based QSP framework is considered in its exact version. All previous achievements are involved in the definition of a new exact QSP algorithm, called EQSP-SRBB, which defines the first known implementation of UCGs as a means of exact SRBB. A classical precomputation step has been added to determine the correct parameters, and the separation strategy is used to minimize the depth. A paper describing this work has been submitted to the RC26 conference, still awaiting review.

Both variational and exact QSP algorithms proposed allow for further optimizations. Thanks to the structure of EQSP-SRBB, it is possible to parallelize the training of the QNN in VQSP-SRBB, overcoming the scalability threshold and reducing the runtime. Moreover, while the OSUN algorithm can be improved adding hardware connectivity constraints and extending ancillary registers, EQSP-SRBB is directly affected by future SRBB optimizations.

n	Time	Error
2	$\sim 9m$	$\sim 10^{-15}$
3	$\sim 16m$	$\sim 10^{-13}$
4	$\sim 33m$	$\sim 10^{-13}$
5	$\sim 1h$	$\sim 10^{-7}$
6	$\sim 2h$	$\sim 10^{-3}$
7	$\sim 5h$	$\sim 10^{-3}$
8	$\sim 11h$	$\sim 10^{-3}$

n	Hellinger	STD
2	~ 0.03	~ 0.02
3	~ 0.11	~ 0.08
4	~ 0.19	~ 0.04
5	~ 0.31	~ 0.05

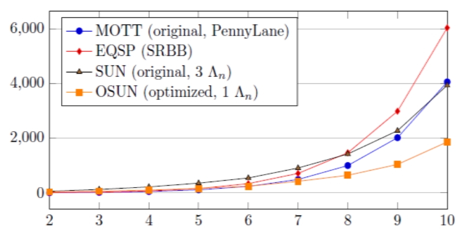

Fig. 1 (left) HPC simulations of VQSP-SRBB with Adam optimizer and Fidelity loss; (center) Results of VQSP-SRBB on real hardware IQM Garnet; (right) Depth vs number of qubits for exact QSP algorithms.

References

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