Compiler Development for Neutral Atom Quantum Computers

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***Abstract*—*Neutral Atoms* (NAs) are an emerging and promising platform for universal quantum computing characterized by high-fidelity, long-range qubit interactions, native multi-qubit gate support, and significant scalability. Recent advancements demonstrate the dynamic rearrangement and shuttling of qubit arrays, enhancing arbitrary connectivity albeit with some time overhead. While the hardware capabilities of NAs rapidly advance, there is a risk that software development lags behind, limiting the exploitation of these capabilities. This work addresses this gap by focusing on two primary software objectives: improving existing quantum circuit mapping tasks and exploring novel solutions such as logical-level routing for fault-tolerant quantum computing. We discuss compilation for hybrid architectures, combining SWAP gate insertion and shuttling-based atom rearrangements and zoned architectures, which divide the architecture into different computational zones to enhance gate parallelism. We discuss the inherent challenges and present efficient algorithmic approaches for each method. The complete code for the proposed solutions is publicly available as part of the *Munich Quantum Toolkit* (MQT).**

I. INTRODUCTION

Neutral Atoms (NAs) have emerged as a promising platform for universal quantum computing [1]–[4], offering a wide range of computational capabilities. These include high-fidelity, long-range interactions between qubits, native multi-qubit gate support [4]–[6], and large scale realizations [7], [8]. Additionally, Bluvstein *et al.* [9], [10] have demonstrated high-fidelity dynamic rearrangement and *shuttling* of qubit arrays during computation, allowing for arbitrary connectivity with some additional time overhead.

In recent years, the software community has increasingly focused on the NA platform, developing various solutions for NA-specific compilation tasks [11]–[14]. Despite rapid experimental advancements, there is a risk that the available hardware may outpace the development of appropriate software solutions, preventing full utilization of the hardware's capabilities [15]. The role of the compiler is to translate high-level quantum algorithms into instructions executable by the hardware, utilizing available quantum gates and operations such as atom rearrangements.

Developers of compilation software aim to maximize the advantages of NA capabilities through two primary objectives:

1) **Improve:** Leverage novel NA features to achieve higher fidelities or shorter circuit runtimes.
2) **Extend:** Identify new tasks or problems where NA capabilities can offer improvements.

This work addresses both objectives and discusses efficient software solutions proposed to tackle these challenges.

First, we introduce compilation for **hybrid architectures**, which combines multiple capabilities or selects the best available option. We explore this approach for quantum circuit routing, where qubit connectivity can be established using either SWAP gates or shuttling operations.

Second, we present **zoned architectures**, which divide the architecture into different computation zones, enabling high gate parallelism among a large number of qubits. This approach does not aim to improve existing compilation schemes but focuses on handling logical qubit arrays and transversal gates within the context of quantum error correction.

For both approaches, we discuss the general concept and fundamental challenges and briefly outline algorithmic solutions. The complete code for the proposed software solutions is publicly available as part of the *Munich Quantum Toolkit* (MQT) [16].

II. CAPABILITIES & CONSTRAINTS

In Neutral Atom quantum computing, qubits are encoded in the electronic states of individual atoms, such as Rb, Sr, or Yb, which are trapped in optical tweezers [7]. These qubits are manipulated using laser beams, with single-qubit gates realized through state transitions driven by a combination of global and local lasers [2], [10]. Multi-qubit gates are implemented via the Rydberg blockade mechanism, which prevents the simultaneous excitation of two nearby atoms to a Rydberg state. This technique enables the creation of fast and high-fidelity CZ-gates [5], [10] on nearby atoms.

Additionally, qubits can be dynamically rearranged during computation by *shuttling* atoms with high fidelity, allowing for arbitrary qubit connectivity [10]. Experimentally, this is achieved using two types of optical traps: 1. *Spatial Light Modulator* (SLM) traps, which define single static trap sites, and 2. *Acousto-Optic Deflector* (AOD) traps. AOD traps are formed by overlapping two 1D AODs (in the x and y directions) to create a 2D grid of trap sites at their intersections [10], [17]. Atoms can be transferred between trap types referred to as *loading* (SLM $\rightarrow$ AOD) and *storing* (AOD $\rightarrow$ SLM). Qubits are shuttled by moving AOD rows and columns, thereby rearranging the trapped atoms. However, this process is constrained by the fixed ordering of rows and columns, meaning they cannot be swapped [15].

While these capabilities and constraints are common to all NA-based architectures, the following section will focus on

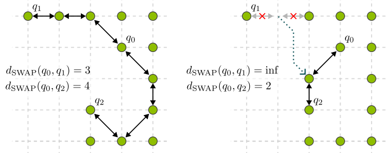

Figure 1. Mapping conflicts for hybrid mapping: The SWAP distance is changed by the shuttling operation.

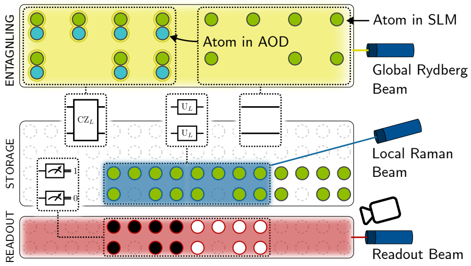

Figure 2. Zoned architecture based on Ref. [9] showing operations on logical qubit patches of 7 qubits each.

two specific hardware setups and tasks: hybrid and zoned architectures.

III. HYBRID ARCHITECTURE

Considering the extensive capabilities of NAs, as reviewed earlier, we encounter a dual mapping problem. First, in the *gate-based mapping* step, gates that are not trivially connected can be routed by modifying the qubit mapping using SWAP gate insertion. Second, in *shuttling-based mapping*, the qubit mapping remains unchanged while the connectivity graph is altered by moving atoms to new trap coordinates.

Concept: We propose a hybrid compilation approach to explore the potential improvements by combining gate-based SWAP insertion *and* shuttling-based atom rearrangements.

Challenges: Utilizing both mapping capabilities significantly increases the number of possible operations during the mapping process, resulting in an increased search space. Additionally, both gate- and shuttling-based mapping directly affect connectivity and can inadvertently conflict with each other. Specifically, shuttling qubits not may also alter the optimal SWAP path for other qubits, as illustrated in Figure 1.

Software Solution: The proposed solution [11] builds on existing algorithms for SWAP gate insertion [18] and adapts them to NA characteristics. This is achieved by comparing the resulting SWAPs with suitable shuttling operations and selecting the better option based on a fidelity and time-aware cost function. This approach allows for fast and efficient compilation, capable of adapting to different hardware settings and choosing the best mapping strategy.

IV. ZONED ARCHITECTURE

Recent experimental breakthroughs have been achieved using a novel zoned architecture, where distinct functionalities (entangling, storage, measurement) are carried out in dedicated, spatially separated zones, with shuttling facilitating the transfer of atoms between these zones [9], illustrated in Figure 2.

Concept: Initially, the qubits are located in the storage zone, which offers optimal coherence times. However, CZ gates can only be performed in the entangling zone. Consequently, the task is to shuttle qubits from the storage zone to the entangling zone and back. This approach applies the architecture to the novel task of routing qubit patches representing single logical qubits. Global gates, combined with parallel shuttling, make NAs a promising hardware platform for this task.

Challenges: The main challenges involve reducing the substantial routing overhead required to move atoms between zones while adhering to the no-crossing AOD constraint. Additionally, the operations must be compatible with fault-tolerance criteria, necessitating special considerations and the simultaneous movement of many physical qubits.

Software Solution: The proposed approach is baded on a modified graph coloring of the interactions. This method schedules multiple entangling gates in parallel and ensures that several sets of entangling gates are applied without intermediate, time-consuming shuttling of atoms between zones. Compared to a naive solution, this approach minimizes the time required for loading, shuttling, and storing the qubits while maximizing the parallel execution of entangling gates.

V. DISCUSSION & CONCLUSION

Neutral Atoms (NAs) present a highly promising platform for quantum computing, especially for fault-tolerant computation. However, rapid experimental advancements risk outpacing the development of appropriate software solutions needed to fully exploit NA-specific capabilities. In this work, we explored how leveraging these capabilities can enhance results for existing tasks such as circuit mapping and facilitate novel approaches like routing at the logical level for fault-tolerant quantum computing. The corresponding software packages are publicly available as part of the *Munich Quantum Toolkit* (MQT) [16] and represent significant steps towards bridging the gap between hardware and software development for NAs.

ACKNOWLEDGEMENTS

This work received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program (grant agreement No. 101001318), was part of the Munich Quantum Valley, which the Bavarian state government supports with funds from the Hightech Agenda Bayern Plus, and has been supported by the BMWK based on a decision by the German Bundestag through project QuaST, as well as by the BMK, BMDW, and the State of Upper Austria in the frame of the COMET program (managed by the FFG).

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