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研究課題名（和文）トポロジカル量子アルゴリズムのためのデータ解析と整合性保証

研究課題名（英文）Data analysis and verification of topological quantum algorithms

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研究成果の概要（和文）：このプログラムの過程で、トポロジカル量子コンピューティングアルゴリズムのコンパイルと最適化に関する5つのソフトウェアパッケージを作成して公開しました。 私たちは、有名なジャーナル、IEEEコンピュータ、サイエンスアドバンス、ACM-XRDSの論文など、国際雑誌や会議の議事録に30以上の出版物を掲載しました。 この研究の期間中、量子回路を重要なメディアの注目を集めるために一般市民を使用するmeQuanics市民科学プロジェクトのプロトタイプデザインを開始しました。 New Scientist、Financial Times、BBCなどのフォーラムでは、

研究成果の概要（英文）：During the course of this program we successfully wrote and published five software packages on the compilation and optimisation of topological quantum computing algorithms. We published over 30 publications in international journals and conference proceedings including papers in the prestigious journals, IEEE Computer, Science Advances and ACM-XRDS. During the period of this research we launched a prototype design of the meQuanics citizen science project that uses the general public to help compile quantum circuits to significant media attention. Over 100 popular media articles in forums such as New Scientist, the Financial Times the BBC and others have appeared based on work conducted as part of this project and we are now actively collaborating with multinationals such as Microsoft and Google and with multiple quantum computing start-up companies as a result of this project. We are now ready to push forward even more rigorously in developing the field of quantum software

研究分野：Quantum Engineering and Software Engineering

キーワード：Quantum Computing　Quantum Error Correction　Topological Computing　Quantum Software　Quantum Compilation　Resource Optimisation

１．研究開始当初の背景

At the beginning this project we had initiated research into the field of quantum software engineering. Rather than focussing on development of new quantum algorithms and applications, we were researching the software packages required to compile, optimise and run large-scale quantum algorithms already in existence. Preliminary work conducted in 2012 indicated that fully error-corrected quantum algorithms would require significant optimisation at the implementation level to reduce quantum resources such as physical qubits and computational time. This field of quantum compilation and optimisation was only in its infancy, with a handful of people worldwide working on classical software packages to operate large-scale computers and communications systems.

Our preliminary work into quantum software engineering exposed a plethora of unsolved problems that could be addressed as part of a research program using a variety of well established techniques in the classical computer science field, such as approaches in citizen science, complexity theory and AI computing and machine learning. Our goal was to take the first steps in this area to construct a framework for classical software control for quantum computing.

２．研究の目的

Our primary purpose in this research was to begin to build classical software compilers for large-scale quantum computing algorithms. Due to the necessity for quantum error correction protocols, the implementation of a large scale algorithm requires complex circuit design and compilation packages to reduce the total number of physical resources needed to successfully implement a large-scale and commercially useful quantum algorithm. Our research methodology consisted of four major approaches.

- Benchmarking a fully error corrected quantum algorithm utilising topological codes for quantum error correction, the most widely adopted approach for large-sale quantum hardware.
- Develop the formalism for fault-tolerant circuit synthesis for high level quantum circuit descriptions. This required the integration of ancillary protocols for a universal, error corrected gate set and integrating in geometric constraints that are specific to quantum hardware models.
- Develop a synthesis method for circuit optimisation for error corrected quantum circuits and derive relevant metrics that can be used to estimate physical resources and targets for optimisation protocols.
- Build classical software programs that allow us to integrate error correction protocols with other high level quantum software packages such as Quipper and Microsofts Liqid package that will produce compiled circuit structures for implementation on actual quantum computing hardware models under experimental development.

Our research methodology leverages many techniques from both the fields of quantum information science and classical software engineering. We have also initiated projects in the field of “citizen science” to initiate research into optimised circuit compilers for topological quantum computation. An initial platform, which we have named meQuanics, was launched online to test out a gameplay interface and determine the viability of a citizen science platform for quantum software engineering and compilation.

３．研究の方法

Our research methodology leverages many techniques from both the fields of quantum information science and classical software engineering. We have also initiated projects in the field of “citizen science” to initiate research into optimised circuit compilers for topological quantum computation. An initial platform, which we have named meQuanics, was launched online to test out a gameplay interface and determine the viability of a citizen science platform for quantum software engineering and compilation.

４．研究成果

We detail our major results in chronological order and restrict our discussion to major software packages we have released as a part of this project. There has been several ancillary results in quantum communications and quantum architecture design that were also published in high profile journals that have been listed in the bibliography that emerged as a consequent of research during this project, but the major focus of this grant was related to developing compilation, optimisation and benchmarking of fully error corrected quantum circuits.

2014

During the first year of this project, we developed three key software package prototypes that will become part of a full quantum software compilation stack:

meQuanics:

The meQuanics project was designed as a citizen science platform to allow the general public to help in developing data heuristics for resource optimisation in topologically error protected quantum algorithms.

Inspired by similar projects in the biological sciences, our research into quantum circuit design and optimisation allowed us to create a simple 3D puzzle game where the goal was to use certain rules to shrink the physical size of a 3D puzzle that represents a full quantum circuit. For a full scale quantum algorithm, these puzzles would be far too large for individual optimisation (by hand or via citizen science techniques) and we strongly believe that the problem in classically intractable to solve. Hence A.I. and/or machine learning techniques need to be employed. For this technique to work, we require a data set of optimisation data for A.I and/or machine learning programs to “learn” from. This is the goal of meQuanics. The initial prototype we developed in 2014 was released to the public to test out and generate feedback and we generated over 20 media articles worldwide about the project, including media in Japan, Australia, the US, Europe and the U.K. The prototype was extremely successful and we are now in a second stage of development, through partnerships with Aarhus University in Denmark and a newly formed quantum computing start up, called Turing inc.

Hardware Translation:

A second major software achievement in 2014 was published in the journal Scientific Reports and presented a hardware translation package that can convert an abstract geometric description of a topological quantum circuit into the specific sets of control sequences needed for each individual physical qubit in a quantum computer. This software package will be a key component that connects together the “offline” and “online” components of the classical software stack for quantum computing. The “offline” component is the compilation and optimisation software needed to prepare a quantum algorithm for implementation (before the quantum computer is initialised) and the “online” component is the dynamic classical code needed to operate the quantum computer during algorithmic computation. This mapping software is currently being integrated with error correction decoding code that we are now building

Verification and Programming quantum computers:

In a series of papers published in Springers lecture notes in computer science, we developed specific code that can be used to verify compiled, error-corrected quantum algorithms and specify the series of software components needed to both program a quantum computer and operate a quantum computer. This framework for quantum software engineering had never been specified before in the context of actual hardware being developed by companies such as Microsoft, IBM and Google and is now a common framework for the newly formed field of quantum software engineering.

2015

A standard representation of error corrected quantum circuits:

In 2015 we successfully formulated a generalised description of arbitrary quantum algorithms which is completely compatible with both quantum error correction and fault-tolerant quantum circuit design. This representation allowed us to being building a full circuit compiler that would allow us to connect high-level quantum algorithmic and programming descriptions (eg. packages such as Quipper and Liqid) with low level error correction protocols, hardware translators and resource optimisers for large-scale algorithms. This initial work, published in Springers lecture notes in computer science, would lead to multiple software packages that would compile arbitrary algorithms into a hardware compatible type of quantum assembly.

A second major result was invited papers at the prestigious engineering conference DAC, the Design Automation Conference. Our paper “An introduction to fault-tolerant quantum computing” appeared in the proceedings of DAC and introduced the classical Automation community to the technical challenges in programming and controlling large-scale quantum computers and communications systems.

2016

2016 was a significant year in this project with a large number of results published in the physics and computer science communities.

IEEE Computer and ACM:

In 2016, we published two significant reviews in quantum software engineering for the computer science community. One was published in the journal IEEE computer and one published in the magazine ACM-XRDS. We introduced the primary classical software components needed to program and control a quantum computer and described how these components will interface with actual hardware under construction. Both of these publications were very well received, with several media articles appearing as a result of these papers.

meQuanics:
Being a citizen science platform for quantum software development, we decided to attempt further fundraising for game development using a citizen science platform known as kickstarter. Kickstarter asks for donations from the general public to complete a specific task or product of interest to internet users. This was a significant milestone in the field of both quantum information and the physical sciences as it was, to our knowledge, the first time anyone had laughed a crowdsourced funding campaign for ostensibly a scientific project. The goal of the kickstarter campaign was to raise $100,000USD in donations to move the meQuanics game to a beta-stage release. The campaign managed to raise approximately $40,000USD in donations, which due to the rules of the kickstarter platform resulted in a failed campaign (you need to raise your target amount in order to receive any funding). While the campaign was a failure it did demonstrate that a project in quantum information science has significant support from the general public and that this platform could be a significant source of scientific funding into the future. We have now initiated more traditional collaborations to continue both work on meQuanics and the entire optimisation platform for quantum compilation.

Topological Assembly:
The meQuanics platform is designed to optimise a specific error correction implementation of quantum circuits, known as topological quantum computation. meQuanics is not designed to compile an abstract quantum algorithm into this “topological form”. In response to this, we released a compilation package called TQEC that will produce a topological quantum circuit from a high level description of a quantum algorithm or circuit. This compiler produces an unoptimised “canonical form” for the circuit. This canonical form needs to be further optimised to reduce physical resources for an actual hardware implementation that is the focus of ongoing research. This software package was published in the journal Scientific Reports and was the focus of several invited international talks in Canada, the U.S. and Europe.

2017

The ICM Compiler:
Released in 2016 and published in the journal, Quantum Science and Technology, in 2017, we successfully implemented the ICM quantum circuit compiler. This compiler will take as input an arbitrary quantum circuit description and output a specific form of this program that is compatible with ANY quantum error correction code that may be used at the hardware level. The ICM formalism takes into account the geometric description of the hardware, the restricted set of quantum gates allowed under an error corrected algorithm and the resources available at the physical level to produce a hardware compatible circuit structure for fault-tolerant error corrected computation.

Lattice Surgery Compiler:
Our initial research was based around a particular logic model of topological quantum computation, known as braiding. There is a second method for performing logical operations at the error corrected level known as lattice surgery that may be easier to compile and optimise. Based upon the ICM compiler formalism, we developed and released a codebase that will compile a large-scale algorithm into a specific operational gate set that can be used in a topological quantum computer, employing the lattice surgery framework. This work was published in the journal New. J. Physics.

Optimisation is NP-Hard:
Our final result in this project was a complexity theory proof that optimising topological quantum circuits lies in the classical complexity class NP-hard. This paper has been released on the arXiv and is currently under review in the journal npj: Quantum Information. Now that we have a theoretical proof on the difficulty of resource optimisation for a quantum computer, we need to address the problem of whether an approximate solution is sufficient or if other non-deterministic optimisation techniques for quantum compilation is possible.

Aside from these specific results related to quantum software engineering, we also published multiple papers in quantum communications and system design as part of this project. These include:

- An architecture for a large-scale quantum computer in Diamond, published in Phys. Rev. X.

- The invention of a quantum communications framework based on physically transporting error corrected memories. Known as a quantum sneaker net. This result was published in Scientific Reports
- An description of how quantum networks of different design can be connected together, published in Phys. Rev. A.
- An experimental paper using the online platform "IBM Quantum Experience", implementing 4 different protocols on a 5 qubit prototype quantum computer. This was published in Phys. Rev. A.
- A large-scale quantum architecture for ion-trap quantum computing, published in Science Advances.
- An analysis of faulty qubit components in an error corrected quantum computer and how this effects resource requirements for a large scale algorithm. This was published in the journal New. J. Physics.
- We co-edited a book published by Springer Lecture notes in computer science based on quantum programming and reversible computation.
- We completed the design and analysis of a diamond based quantum communications network. Results published in Phys. Rev. A. and Scientific Reports.

５．主な発表論文等
（研究代表者、研究分担者及び連携研究者には下線）

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10. S.J. Devitt. Performing Quantum Computing Experiments in the Cloud. Phys. Rev. A. **94**, 032329 (2016). Peer Reviewed. DOI: 10.1103/PhysRevA.94.032329.
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〔学会発表〕（計 10 件）

1. **03-Dec'16.** S.J. Devitt, Invited: Quantum hardware and software engineering. Conference on post-quantum cryptography, University of Chongqing, Chongqing, China.
2. **27-Nov'16.** S.J. Devitt, Invited: The current state of quantum computing and citizen science for quantum software. Summit on Human Problem Solving and Artificial Intelligence, Sondorborg, Denmark.
3. **11-Jun'16.** S.J. Devitt, Invited: Simulating molecular vibrations with a superconducting boson sampling quantum computer. Japan Science and Technology Agency (JST), Building 6, Kyoto University, Japan.
4. **18-Apr'16.** S.J. Devitt, Invited: (Software) meQuanics: The Quantum Computer Game. Quantum Computer Science, Banff International Research Station, Canada.
5. **19-Apr'16.** S.J. Devitt, Invited: Initial Optimisation algorithms for topological quantum computing. Quantum Computer Science, Banff International Research Station, Canada.
6. **25-Jun'15.** S.J. Devitt, Invited: Compilation for time-optimal, fault-tolerant quantum circuits. Quantum Programming and Circuits Workshop, IQC, Waterloo, Canada.
7. **28-Jun'15.** S.J. Devitt, Invited: Introduction to Fault-Tolerant Quantum Computing. Design Automation Conference (DAC'52), San Fransisco, U.S.A.
8. **11-Feb'15.** S.J. Devitt, Invited: Programming a Topological quantum computer. QI Workshop, Physics and Information in Quantum Information Science, Main building, National Institute of Informatics, Tokyo, Japan.
9. **10-Jul'14.** S.J. Devitt, Keynote: The Classical Control of Large Scale Quantum Computers. 6th International Conference on Reversible Computation (RC2014), Building 6, University of Kyoto, Kyoto, Japan.
10. **15-Jun'14.** S.J. Devitt, Contributed: The Quantum Memory Stick and the Quantum Sneakernet. Conference on Lasers and Electro-Optics 2014 (CLEO), San Jose, USA.

〔図書〕（計 1 件）

1. S.J. Devitt and I. Ianese (Eds.). Reversible Computation, Lecture Notes in Computer Science (LNCS) 9720 (2016). **DOI**: 10.1007/978-3-319-40578-0

6 研究組織

(1)研究代表者

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