Solutions logicielles pour l'optimisation des programmes et ressources quantiques

Software-based quantum program and resource optimisation (SoftQPRO)

I. Context, positioning and scientific objectives

Context. Quantum computers can theoretically solve problems out of reach of classical computers. The British NQIT and Dutch QuTech programs, the announced European flagship on quantum technologies, and the availability on the market of new (and more convincing) D-Wave machines are witnesses that quantum computing is entering a new area. At the national level, Atos-Bull publicly announced earlier this year they are embarking on the quest of the quantum computer. CEO Thierry Breton supported the european flagship to EC President Juncker and Atos is represented at the flagship High Level Steering Committee in the person of Cyril Allouche, Atos R&D director and partner of the present project. In July, Simon Perdrix (coordinator of the present project) co-organized a workshop at ministry of research which emphasized, according to T. Calarco (Flagship leader) and P. Indelicato (*Dir. Cabinet* of Minister T. Mandon), the strength of the french community in the computer science approach to quantum technologies.

Objectives. Quantum Computing is still in its infancy and several technologies are competing (ion trap, supra conductor, solid state, optic…) for the implementation of the quantum computer. We aim at filling the gap between the theoretical quantum algorithms and these various technologies. Our *software-based quantum program and resource optimisation* project aims at easing the crucial back and forth interactions between the theoretical approach to quantum computing and the technological efforts made to implement the quantum computer. For instance, program optimisation could depend ultimately on the actual chosen technology, and conversely, the use of a given technology could be driven by the particular quantum algorithm one wants to implement. Classical simulation is central in the development of the quantum computer, on both ends: as a way to test quantum programs but also as a way to test quantum computer prototypes. For this reason we aim at developing sophisticated simulation techniques on classical high-performance computers (HPC).

Our approach. Any quantum algorithm can be expressed in a high level quantum programming language: a large library of quantum algorithms [GLR+13,VRS+15] have been written in Quipper, an open source language co-developed by Benoît Valiron (a partner of the project). In Quipper, only compilation to quantum circuits has been considered so far, but they can potentially be compiled for other targets depending on the computational model (unitary-based or measurement-based) and the hardware technology. Another interesting target is a simulation on a classical (high performance) computer. Our project aims at developing software-based quantum program and resource optimizations. The resources to optimize are typically the number of instructions, the size of the memory, the depth (parallel time), or the amount of entanglement for instance.
Our approach is based on a compilation pipeline: From Quipper programs to an intermediate language (ZX-calculus) and then to quantum hardware or HPC simulation.
Work-package 1. At the front end, we aim at developing high level techniques based on program static analysis like abstract interpretation or implicit computational complexity to optimize various resources. These techniques are successfully and massively used for classical code optimization and resource saving, whereas only a few proofs of concept exist in the quantum case [P08,DMZ10].
Work-package 2. Intermediate graphical language. Our original approach relies on the use of an intermediate formal graphical language the ZX-calculus [CD09], equipped with a powerful equational theory, as an ideal common denominator for resource optimization.
Work-package 3. At the back end, specific optimizations depending on the computational model or quantum technologies are considered. A particular attention will be paid to simulation by means of HPC.

Originality in relation to state of the art. The project is innovative in its form as it is one of the first ANR collaborative projects with an industrial partner in quantum computer science. Regarding the state of the art, some papers [PRS15,SRSV14,YG07] address the question of the optimization of the circuits produced by compiling programs written in Quipper or other languages. We go beyond this with a compiling pipeline, several targets and an intermediate language. The project is also innovative on the methods: only a few proofs of concept on the use of static analysis for quantum programs have been published (entanglement analysis [P08], implicit computational complexity [DMZ10]), we aim at refining these techniques leading to efficient tools for program analysis.

Feasibility, methods and risk management. Each class of tools that we propose to use is already at least partially developed and has demonstrated its suitability for the use we want to do:
• Quipper already allows encoding of algorithms for nontrivial size problems, and comes with a library of all the main quantum algorithms already encoded in this language. Benoît Valiron, member of the project, participated to this great effort.
• Static analysis, abstract interpretation, implicit computational complexity and code optimization techniques are used in the compilation of conventional languages. Worldwide specialists of classical static analysis [GMR12,MP09] are involved in this project.
• ZX-calculus is a well developed formal graphical language with a powerful equational theory which has been already successfully used in several domain of quantum information theory (quantum protocols [AB04], measurement-based quantum computation [DP10], foundations [CDKW12]). Quantomatic is a dedicated open source software allowing ZX-diagrams representation and transformations. In particular strategies can be defined in this software.

II. Project organisation and resources

Scientific coordinator. Simon Perdrix is a 36 year old CNRS researcher. He strongly contributed to the development of the ZX-calculus: from the early age [DP09,DP10], when he was working in the quantum group in Oxford when and where the ZX-calculus has been invented [CD09]; to the recent developments of the language, answering one of the main open question in this field [PW16]. By introducing the first static analysis techniques for quantum programs at SAS'08 [P08], he made a proof of concept of the software-based approach aimed to be refined in the project. He is also an expert of Measurement-based Quantum Computation one of the most promising model for a physical implementation of the quantum computer. He has over 40 refereed publications (ICALP, QIP, MFCS, ISAAC, SAS, FCT...). He leads the Quantum Computation french network (GT IQ) at CNRS GdR IM and is board of the CNRS Quantum Technology network (GdR IQFA). He has been PI of several projects (PEPS, Region Lorraine), and led work-packages in ANR and EU STREP projects. In 2016, he has been elected scientific secretary of section 6 at CoNRS. Section 6 is in charge, among other expertise duties, of hiring, promoting, and evaluating CNRS researchers in computer science.

Consortium. The consortium has 2 academic (LORIA and LRI) and 1 industrial (Atos-Bull) partners. LORIA brings experts in quantum computing, ZX-calculus, measurement-based quantum computing and program analysis, including experts in (classical) implicit computational complexity. LRI brings the complementary expertise on quantum programming language, and HPC. Since Atos-Bull announced embarking on the quest of the quantum computer earlier this year, the effort of Atos-Bull is the equivalent of 10 researchers, and 2 CIFRE PHD students, in a R&D group led by Cyril Allouche. Academic collaborations between partners at LORIA and LRI has already been initiated with joint publications [ADP+14,DPTV14] and joint project participation (Stic AmSud FoQCoSS). An Atos-LRI CIFRE PhD started this fall on quantum programs and HPC-based quantum circuit simulation, whereas an Atos-LORIA CIFRE PhD will start in the next few months on the subject of the present project. Atos will provide to the partners an access to its HPC infrastructure. The researchers involved in the consortium are:

Partner	Permanent members	Involvement	Non-Permanent
LORIA	Emmanuel Hainry (MCF Univ. Lorraine) Emmanuel Jeandel (Prof Univ. Lorraine) Jean-Yves Marion (Prof IUF & Univ. Lorraine, Head of LORIA) Romain Péchoux (MCF Univ. Lorraine) Simon Perdrix (CR CNRS) *Scientific Coordinator*	25% 40% 20% 25% 65%	Renaud Vilmart (PhD) X[1] (Atos-LORIA CIFRE PhD)
LRI	Marc Baboulin (PU Paris-Sud) Thibaut Balabonski (MCF Paris-Sud) Chantal Keller (MCF Paris-Sud) Benoît Valiron (MCF CentraleSupelec) *site leader*	25% 10% 10% 65%	Timothée Goubault de Brugière (Atos-CIFRE PhD)
Atos-Bull	Cyril Allouche's Group on Quantum Computing		

1 Atos-LORIA CIFRE PhD will start in the next few months.

Budget. HPC platform will be made available to all the partners by Atos. A small additional material investment will however be needed. Meetings between the partners will be organised to help to develop synergy. To supplement the workforce at the two academic partners, a support for a co-supervised PhD on quantum program static analysis, and two postdocs positions are requested: one to reinforce compilation and HPC simulation at LRI, and one at LORIA on optimisation and transformation in the intermediate language.

A total budget of 569k€ is requested over 48 months: 315k€ for academic partners, 254€ for Atos-Bull. Each academic partner will have 3k€ for consumable (computers), 7k€ for graduate level interns, 70k€ for funding 1 year of postdoc. Regarding travel (including visits within the consortium and conference trips) LORIA site asks for 27k€ and LRI site for 18k€. The coordinating site asks for 100k€ for a co-directed PhD and 10k€ for organising two international workshop during the period. Atos Bull requests 254k€ corresponding to 25% of 2 full time researchers + 5k€ for travel + 50k€ of consumable (FPGA Stratix cards, HPC blades) ie., 25% of 1 018 466€.

III. Impact of the project

Scientific, economical, and social impact. Quantum computing is an emerging technology which may have important implications in the economic and social fields: HPC, big data, cryptography. The emergence of powerful quantum processors in the coming years will be a major technological leap, which will give a considerable competitive advantage to players who have anticipated this revolution, while the emergence of new opportunities for economic development, mainly in the field of software. The work proposed in this project are part of this planning effort and innovation, improving the known techniques for quantum simulation and programming, while exploring new areas of innovation.

Meet the challenges of the Défi. Défi 7 and more generally the ANR work program, wishes to contribute to the European research construction. This project aims at building a strong leading team, gathering both academics and industrials, ready for the upcoming Flagship on Quantum Technologies and QuantERA ERA-NET Cofund in Quantum Technologies mentioned in the ANR work plan.
Envisioning the implementation of a quantum algorithm is not a simple task. The backend is still elusive, the sizes of quantum circuits for realistic input sizes are daunting, and there are as of yet very few tools to obtain guarantees on the run of the algorithm and on the results. The development of a compilation platform for quantum computation lies therefore well within the axis “software engineering” (Defi 7 – Axe 3 : Science et technologies logicielles). The objectives of the project are aligned with the three main themes of the axis. The first theme is concerned with computing platforms. In the context of quantum computation, such platform are yet to be designed: one of the goal of the project (work-packages 2 and 3) is to capitalize on the features of each backend to get the best results. The second theme focuses on methods and conception tools for software: this is the realm of work-package 1, devoted to the development of the quantum programming language Quipper. Work-package 1, together with work-package 2 tackles the question asked in the last theme: the validation of software. We aim at developing a toolbox for the certification and the verification of properties of quantum programs.
If the core of the work fits within the 3rd axis of Defi 7, the project also reaches two other axes. Indeed, the development of this compilation tool-chain will require the use of theoretical apparatus: implicit computational complexity, type theory, abstract interpretation, … leading to Axis 1 (Informatique théorique). The LRI and LORIA sites are strong in this aspect. Also, because one of the back-end we have in mind is the emulation of quantum computation, this falls in the realm of Axis 6 (Simulation numérique). This aspect is backed up by Atos and LRI.

Dissemination of results. We envision three means of diffusion and promotion of the results:

1. We will develop a compilation suite consisting in open source tools, some of them incorporated within the Quipper compiler. This compiler is used both by academics and industrials.
2. We plan to publish our results in top conferences and journals, but also communicate at seminars, workshops. Dissemination in popular science will also be done.
3. We aim at gathering the international community around these questions during the project, and we ask a pool of funding to account for this (see above).