Proposal Title: Dataflow computing for continuous real-time adaptive radiotherapy

Lead Supervisor 1 (Main Contact)*
Name: Uwe Oelfke
Institution/Department: ICR / Joint Department of Physics
Email: uwe.oelfke@icr.ac.uk
Phone number: 020 8916 6221

Lead Supervisor 2
Name: Wayne Luk
Institution/Department: Imperial College / Computing
Email: w.luk@imperial.ac.uk
Phone number: 020 7494 8313

Additional Supervisor
Name:Simeon Nill
Institution/Department: ICR Joint Deparmtent of Physics
Email: Simeon.nill@icr.ac.uk

Additional Supervisor
Name: Vitali Averbukh
Institution/Department: Imperial College / Physics
Email: v.averbukh@imperial.ac.uk

Proposal outline

Advances in real-time adaptive radiotherapy promise improved patient outcome, by adapting the delivered radiation to the actual patient anatomy during treatment [1]. While Monte Carlo (MC) simulation methods have shown to provide superior accuracy in calculating physical dose distributions for radiotherapy, the clinical application of MC methods is limited by long simulation times required to achieve a level with sufficient statistical precision. Analytical dose calculation methods, although capable of running faster, are liable to introducing physical approximation compromising the accuracy particularly for heterogeneous tissues such as lung tissues. In such cases, Monte Carlo simulations that are known to deliver reliable dose distributions would be particularly warranted.

The aim of this project is to develop a real-time Monte Carlo simulation system based on dataflow computing engines, which can support continuous real-time adaptive radiotherapy. The research will pioneer a new generation of radiotherapy systems with the potential of revolutionising cancer treatment by their capability of accurately adapting to patient anatomy and to patient conditions in real time, while allowing them to be exploited by medical professionals who may not be experts in high-performance computing or reconfigurable hardware.

Dataflow computing engines involve field programmable gate arrays (FPGAs), which are state-of-the-art reconfigurable hardware devices increasingly used in speeding up demanding software applications. Many cloud providers, such as Amazon and Microsoft, are offering FPGAs as acclerators for demanding computational tasks.

Monte Carlo (MC) simulations have shown to provide the most accurate dose calculations for radiation therapy planning and reconstruction of delivered patient doses. High accuracy is achieved by simulating the physics of a large number of particles in the patient's body. Pathway and interaction of photons and generated electrons are precisely simulated, producing values of the deposited dose in patients with a very low statistical uncertainty. This is in contrast to most analytical methods, which approximate the physical processes of dose deposition. While the MC simulation is able to calculate the interaction of particles accurately within the given geometry, most analytical methods apply macroscopic models which are unable to reproduce specific effects of the dose-tissue interaction. Furthermore, MC simulations are currently the only reliable method which can precisely describe the influence of a strong magnetic field on the tracks of secondary electrons as found in the MR-Linac (MRL).

Our team at Imperial College developed an FPGA-based Monte Carlo design which was over 163 times faster and 170 times more energy efficient than a conventional multi-core software implementation [2]. A fast Monte Carlo simulation for radiotherapy dose calculation targeting parallel CPU-based architecture was developed by our team at ICR [3]. This team also successfully demonstrated the scaling of such architecture to a high degree of parallelism [4], and a related speed-optimised energy/mass transfer mapping method [5]. Our team at Imperial College has shown how multi-level MC designs based on dataflow computing engines for FPGAs can be produced automatically from a high-level description [6], and will build on this work for automating the development of MC simulation for real-time adaptive radiotherapy applications at ICR.

The three objectives of this project are:

1. To enhance the performance of Monte Carlo simulations targeting real-time adaptive radiotherapy, by developing optimised designs for dataflow computing engines based on the latest field-programmable gate array (FPGA) technology for such Monte Carlo simulations;
2. To prototype experimental platforms targeting such optimised dataflow computing engines, to enable the exploration of continuous online tracking and evaluation of the actual delivered dose during the treatment process as well as online re-planning scenarios;
3. To significantly improve the ease-of-use of dataflow engines by automating their optimised design generation from a high-level description; such descriptions would enable medical professionals involved in radiotherapy and imaging without experience in high-performance computing or in reconfigurable hardware to exploit the capability of advanced dataflow computing.

The proposed research promises significant scientific, engineering and clinic impact. Its scientific impact stems from development of novel techniques for fast Monte Carlo calculations targeting adaptive radiotherapy in particular; indeed, such techniques can be extended to cover a wide variety of Monte Carlo calculations in scientific computing. Its engineering impact stems from the first demonstration of design techniques and tools for creating real-time Monte Carlo systems for a key medical application, which can be generalised for other applications involving Monte Carlo modelling. Its clinical impact rests on the development of a new generation of radiotherapy treatments capable of significantly improving their effectivess by continuous accurate adaptation to patient anatomy and to patient conditions in real time.

Feasibility

The feasibility of the proposed project is demonstrated by an initial simplified prototype, resulting from a Cancer Research Centre of Excellence (CRCE) Collaborative Pilot Project Grant awarded to the investigators. This prototype shows that it is possible for a dataflow computing engine to support Monte Carlo simulation of 100 million particles per second to achieve statistically relevant sample size. The proposed research will be able to build on the insights and experience obtained from this prototype.

The project contains three stages, each addressing one of the three objectives described earlier.

Stage 1: Month 1-12. This stage concerns performance enhancement of Monte Carlo simulations for adaptive radiotherapy. New compile-time and run-time design optimisations for dataflow computing engines for such Monte Carlo simulations will be developed, based on the latest field-programmable gate array (FPGA) technology.

Stage 2: Month 13-30. This stage concerns prototyping experimental platforms for optimised dataflow computing engines in Stage 1, to enable the exploration of online tracking and evaluation of the actual delivered dose during treatment, and online re-planning scenarios.

Stage 3: Month 31-48. This stage concerns novel techniques and tools for automating the generation of designs in Stage 2 for dataflow computing engines from a high-level description, to improve the quality of such designs while enhancing the productivity of their users; such techniques and tools will be extensively refined to enable medical professionals involved in radiotherapy and imaging, who may not be experts in high-performance computing or in reconfigurable hardware, to exploit the capability of advanced dataflow computing.

Multidisciplinary approach

This project is strongly multidisciplinary, involving supervisors from ICR and from Imperial College Computing and Physics Departments, as well as significant industrial support by Maxeler Technologies.

Professor Uwe Oelfke is the Deputy Head of the Division of Radiotherapy and Imaging, the Head of the Joint Department of Physics (ICR and RMH), and the Team Leader of the Radiotherapy Physics Modelling group. He is combining recent developments in cancer biology, cancer therapeutics and medical physics in order to improve radiotherapy treatment and planning. He will be the Primary Supervisor of the PhD student, and will be responsible for training the student to cover the relevant topics in cancer biology, clinical radiation therapy and medical radiation physics.

Professor Wayne Luk FREng, Professor of Computer Engineering at Imperial College Department of Computing and former Visiting Professor at Stanford University, has pioneered many advances in accelerating demanding computations in bioinformatics and other applications. He is an experienced supervisor and has graduated over 30 PhD students from Imperial and Oxford. He will contribute to novel dataflow computing technologies for Monte Carlo simulation with both high performance and high energy efficiency for this project. He will be the Associate Supervisor of the PhD student, and will be responsible for training the student to cover the relevant topics in high-performance computing and field-programmable technologies.

Dr Simeon Nill is the Head of Translational Radiotherapy Physics at ICR/RMH. He will ensure that the student is introduced to the current Monte-Carlo algorithms developed in Professor Oelfke’s team. He also will provide benchmark-data for MC simulations in current commercial treatment planning systems, and will lead the clnical assessment of the developed high performance MC platform.

Dr Vitali Averbukh is Reader in Molecular Physics at the Imperial College Department of Physics. His research involves fundamental electronic processes that occur in molecules and clusters following excitation and/or ionisation, which are of high practical importance for estimation and understanding of the radiation damage done by high-frequency radiation. He will be an Additional Associate Supervisor for the PhD student, and will be responsible for training the student to cover the relevant topics in physics.

Professor Georgi Gaydadjiev, from the Imperial College Department of Computing and Maxeler Technologies (Director of Maxeler IoT-Labs and former VP of Dataflow Software Engineering), has significant research experience in academia and in industry. He will contribute to developing tools for dataflow computing, particularly for efficient Monte Carlo simulation.

The project has strong support by the industrial partner, Maxeler Technologies, a London-based high performance computing company spearheaded the dataflow architecture approach to supercomputing data centres and, more recently, to cloud computing with Amazon. Maxeler supports an extensive University Programme of which Imperial College is a leading founding member. For this project, Maxeler will provide free-of-charge full access to its dataflow computing facilities, tools and methodologies and free full access to all the proprietary software resources required for developing the intended dataflow applications. Maxeler Dataflow Software Engineering Department will allocate the required technical personnel time to training, advising and guiding the project team. The in-kind contribution by Maxeler to this project is estimated to be up to £20,000 per year.

The proposed PhD student will be based in ICR in the group led by Professor Oelfke, to enable the student to gain a deep understanding of the theory and practice of adaptive radiotherapy by working closely with those responsible for many exciting advances in adaptive radiotherapy. This will also facilitate the interactions with the medical professionals who will be the end users of the enhanced radiotherapy systems resulting from this research, to make sure a thorough appreciation of their requirements as well as the latest advances of radiotherapy treatment.

The student will have a shared desk in the Computing and Physics Departments at Imperial College. It is envisaged that the student will spend about two to three days per week in the Custom Computing Research Group at Imperial College led by Professor Luk, to benefit from interacting with a world-leading team focusing on dataflow computing and application acceleration. The student will also be able to spend time in the Imperial College Department of Physics and in Maxeler Technologies, working with relevant researchers and industrial professionals whenever it becomes beneficial to do so. There will be bi-weekly project meetings involving the student, the Primary Supervisor and the Associate Supervisors, to monitor progress and to ensure appropriate cross fertilisation of ideas. In addition, monthly reviews will offer opportunities for detailed progress assessment, and for adapting the direction of research should that be necessary.

Literature references

[1] Assessment of MLC tracking performance during hypofractionated prostate radiotherapy using real- time dose reconstruction, MF Fast, CP Kamerling, P Ziegenhein, MJ Menten, JL Bedford, S Nill, U Oelfke, Physics in medicine and biology 61(4):1546-62, 2016

[2] A mixed precision Monte Carlo methodology for reconfigurable accelerator systems GCT, Chow, AHT Tse, Q Jin, W Luk, PHW Leong, DB Thomas, ACM/SIGDA International Symposium on Field Programmable Gate Arrays, 2012

[3] Fast CPU-based Monte Carlo simulation for radiotherapy dose calculation, P Ziegenhein, S Pirner, CP Kamerling, U Oelfke, Physics in medicine and biology 60(15):6097-111, 2015

[4] Towards real-time photon Monte Carlo dose calculation in the cloud, P Ziegenhein, I Kozin, CP Kamerling, U Oelfke, Physics in Medicine and Biology 62(11):4375-89, 2017

[5] Real-time energy/mass transfer mapping for online 4D dose reconstruction, P Ziegenhein, CP Kamerling, MF Fast MF, U Oelfke, Sci Rep., 8(1):3662.1-10, 2018

[6] A domain specific language for accelerated multilevel Monte Carlo simulations, B Lindsey, M Leslie, W Luk, IEEE International Conference on Application-specific Systems, Architectures and Processors, 2016

Advertising details

(Key words or short phrases that students might type into search engines for PhD projects similar to yours).

1. Radiotheraphy
2. Real-time
3. Monte Carlo
4. Hardware acceleration
5. FPGAs
6. Dataflow computing

Project suitable for a student with a background in:

Please tick all that apply:

☒ Life Science
☒ Clinical Science
☐ Chemistry
☒ Computer Science
☒ Physics or Engineering
☒ Mathematics, Statistics, Epidemiology
☐ Other (please detail below)