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ICR The Institute of Cancer Research | Imperial College London

Accelerating volumetric MR Imaging for Real-Time Adaptive Radiotherapy

Supervisors:

Dr Andreas Wetscherek. Joint Department of Physics, The Institute of Cancer Research and the Royal Marsden NHS Foundation Trust

Professor Wayne Luk. Department of Computing, Imperial College

Katharine Aitken Department of Radiotherapy, The Institute of Cancer Research and The Royal Marsden NHS Foundation Trust

Project outline

This project covers research at the convergence of clinical science, engineering and physics in the field of real-time adaptive treatment and therapy monitoring.

The ICR/RMH team have pioneered MR-guided radiotherapy on the UK's first MR-Linac system, enabling daily updated treatment planning based on imaging tumour and organs-at-risk right before treatment delivery. However, to exploit the MR-Linac's full potential and to enable next-generation tumour tracking and treatment delivery strategies, low-latency volumetric real-time imaging is required [1]. Currently available real-time imaging on the MR-Linac is limited to five two-dimensional images per second with latencies up to 350 ms [2], which cannot support simultaneous tracking of tumour and organs-at-risk.

The Imperial team have contributed techniques for accelerating computations based on dataflow computing and FPGA technology (see http://cc.doc.ic.ac.uk). They have shown that 3D image registration can be accelerated to run over 108 times faster than the corresponding software implementation [3]. Their approach can outperform supercomputer nodes [4], and can cover fast MR image processing for cardiac electrophysiological intervention [5]. Moreover, they have demonstrated the potential of FPGA-based dataflow engines for real-time adaptive radiotherapy simulation to support dose calculation [6].

This project will develop a novel approach to real-time adaptive MR-guided radiotherapy by accelerating MR imaging developed by the ICR applicant through dataflow computing techniques pioneered at Imperial. Uncertainty in the exact location of tumour and organs-at-risk leads to the requirement of fractionated delivery and treatment margins, which could prevent the delivery of curative radiation doses for example in the case of pancreatic cancer [7,8]. We will make real-time adaptation in MR-guided radiotherapy possible by characterising motion of both tumour and organs-at-risk with low latency and high throughput. This will enable us to realise the potential of next-generation MR-guided radiotherapy to revolutionise cancer treatment by providing unprecedented certainty needed to deliver precision treatment with reduced margins. This will not only lead to increased treatment efficacy by improving local tumour control without increased toxicity, but also enable hypofractionation, leading to shorter treatments.

This project has three objectives.

1. To define clinical requirements of real-time adaptive MR-guided radiotherapy in terms of temporal and spatial resolution and image orientation regarding the MR image reconstruction. Throughout the treatment delivery these requirements will vary because, for example, the radiation will be delivered from a different beam angle. Accordingly, a volumetric MR image acquisition strategy will be chosen to meet these requirements for imaging multiple target and risk structures, thus enabling real-time adaptive radiotherapy.

2. To prototype an experimental dataflow computing engine for MR image reconstruction and interface it with the MR-Linac system at the ICR to maximise the clinical benefits. This will provide the imaging information for real-time adaptive radiotherapy by locating target and risk structures with high spatio-temporal resolution. To enable continuous treatment adaptation, the MR image reconstruction engine will be integrated with an accelerated dose calculation engine (developed by another Imperial-based PhD student).

3. To significantly improve the ease-of-use of dataflow engines for MR image reconstruction by automating their optimised design generation from a high-level description; such descriptions would enable medical professionals involved in radiotherapy and imaging, but without experience in high-performance computing or reconfigurable hardware, to exploit the capability of advanced dataflow computing to accelerate image reconstruction and improve spatial accuracy.

The proposed approach involves FPGA-based dataflow computing for accelerating real-time MR image processing. FPGA-based acceleration is available from cloud providers including Amazon and Microsoft. Compared to technologies such as GPUs (Graphics Processing Units), our approach has the following benefits. (i) FPGAs can support designs with both low latency and high throughput [9], while GPUs can typically cover one at the expense of the other [10]. (ii) FPGAs are often more energy-efficient with performance comparable to or better than GPUs [3], especially for real-time applications. (iii) FPGAs enable advanced image reconstruction techniques not feasible with current CPUs and GPUs. For example, the direct inclusion of gradient non-linearity and magnetic field inhomogeneity corrections into real-time image reconstruction, as depicted in Fig. 1, would enhance image quality [11] and resolve the dosimetrically-relevant patient outline more accurately.

Our plan is to start this project on 1 October 2021. Dr. Wetscherek will lead the ICR team while Professor Luk will lead the Imperal team.

This project is timely in two ways. First, it will build on a recent study supported by a CRCE Collaborative Pilot Project Grant awarded to the investigators. This study assesses the potential of accelerating 4D MR image processing based on the open-source GRASP MATLAB code [12]. Profiling results identified the bottlenecks within the MR image reconstruction and how FPGA-based dataflow implementations could achieve the desired performance.

Second, the proposed PhD student would work closely with Marco Barbone, a CRUK-supported PhD student focusing on accelerating dose calculations for radiotherapy planning and reconstruction of delivered patient doses, and Rosie Goodburn, a PhD student at ICR working on creating 4D synthetic CT images for thoracic MR-guided radiotherapy planning. These PhD students would work together on integrating real-time imaging and dose calculation computations to support continuous real-time tumour tracking, guiding treatment with minimal latency and enabling real-time dose verification for target structures and risk organs.

In addition to developing an experimental platform to enable real-time adaptive radiotherapy, this research will pioneer automatic generation of advanced dataflow designs for such computations. Relevant techniques including mixed precision representations [13] will be studied; the automation of designs to support, for example, motion compensation for artefact-free MR imaging [14], will also be investigated.

To maximise the clinical benefits of this project, the student will work closely with medical professionals led by Dr. Aitken at ICR/ RMH, who will: (a) provide functional and performance requirements for real-time MR imaging, and (b) evaluate the prototypes resulting from the project. This will be clinically focused on applying the technology to abdominal radiotherapy (pancreas and liver) where facilitating tumour tracking combined with daily plan adaptation would be predicted to significantly enhance the therapeutic ratio. The evaluation will enable the prototypes to be enhanced, so that they can contribute to both clinical treatment improvement and progress in cancer research.
Feasibility

The project builds on a successful CRUK Major Center Development fund project, in which a prototype was developed to accelerate 4D MRI processing. The MRI data sampling bottleneck can be overcome by including motion information into image reconstruction [14], with low-rank motion-models allowing for motion estimation with high temporal resolution [15]. This project covers these advances, with three stages addressing the objectives described earlier.

Stage 1: Month 1-12. This stage focuses on MR image acquisition and reconstruction and the MR-guided radiotherapy workflow, including detailed requirements of MR imaging for real-time adaptive radiotherapy. Suitable MR acquisition strategies for volumetric real-time MRI will be identified, taking into account optimisations for FPGA-based dataflow computing.

Stage 2: Month 13-30. This stage concerns prototyping experimental platforms for dataflow computing, tailored to the MR data acquisition strategy identified in Stage 1. These prototypes will be integrated with the MR-Linac to enable: (a) creation of low-latency images with high spatial accuracy for real-time MR-guided radiotherapy adapted to patients' exact position and anatomy, and (b) continuous real-time tracking of target and risk structures during the treatment process, which will be integrated with accelerated dose calculation.

Stage 3: Month 31-48. This stage concerns automating the generation of dataflow computing engines for MR image reconstruction, such as the ones employed in Stage 2 from a high-level description, to improve design quality and user productivity. Such automation will enable medical professionals involved in radiotherapy and imaging, who may not be experts in computing or hardware, to exploit advanced dataflow computing.

Literature references
(Provide a bibliography of any cited literature in the proposal).

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Key words

1. MR-guided Radiotherapy
2. Real-time adaptive
3. MR image reconstruction
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)

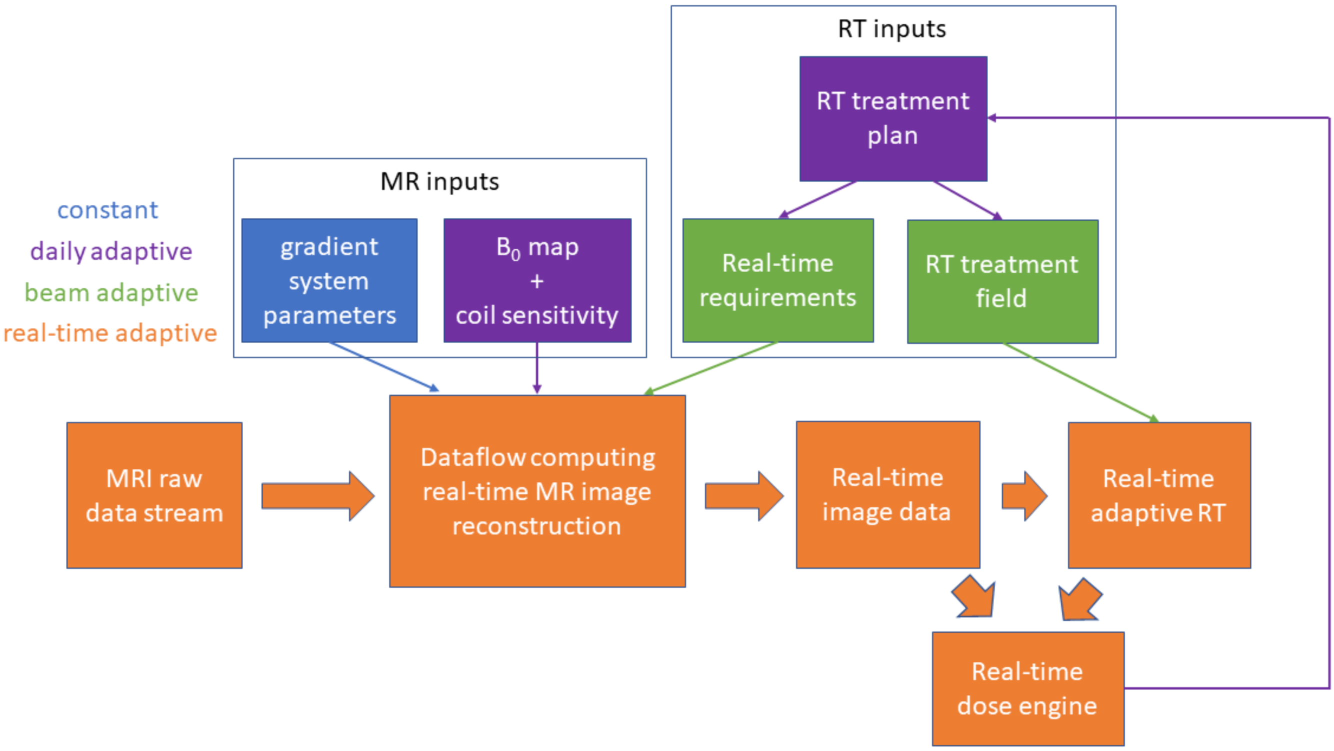

Figure 1: Vision for real-time adaptive MR-guided radiotherapy (RT): At the core the proposed dataflow computing real-time MR image reconstruction, which generates real-time image data from the MRI raw data stream. Not only the constant system parameters (blue), and the day-to-day varying (purple) MR properties, such as B_0 map and coil sensitivities are taken into account, but tailored real-time image data is generated according to the beam

adaptive (green) requirements for guiding the delivery of the current segment. This enables real-time adaptive (orange) radiotherapy with high spatio-temporal fidelity allowing for reduced margins and number of fractions. Real-time image data and delivered radiation are monitored by the real-time dose engine, enabling safe delivery and updating of the remaining RT treatment.

Person specification:

This project is suitable for a talented graduate or undergraduate student with computer science, engineering, physics or mathematics, statistics or epidemiologybackground. The standard minimum entry requirement is a relevant undergraduate Honours degree (First or 2:1) and our full eligibility criteria can be found here: https://www.icr.ac.uk/studying-and-training/phds-for-science-graduates/entry-requirements

The studentship will be registered at the Institute of Cancer Research with affiliate status at Imperial College London. The student will have access to both institutions and benefit from the world class research infrastructure and expertise across the two institutions. The student will become a member of the CRUK Convergence Science Centre PhD cohort which is a unique group of students working across distinct disciplines to tackle the big problems in cancer. A unique convergence science training programme will provide the skills and language to navigate different disciplines.

Funding and Duration:

Studentships will be for four years commencing in October 2021. Applications for PhDs are invited from talented UK graduates or final year undergraduates. International students are also invited to apply subject to outlining how they will meet the difference in tuition fees.

We look forward to receiving applications from all candidates and will select those who display the potential to become the world leading cancer researchers of the future based on their application and performance at interview. However, we are particularly to welcome UK applicants from Black and ethnic minority backgrounds, as they are underrepresented at PhD level within the ICR and Imperial.

Successful candidates will undertake a four-year research training programme under the guidance of a supervisory team of world-class researchers. Students will receive an annual stipend, currently £21,000 per annum, and project costs paid for the four-year duration. Convergence Science PhDs cover tuition fees for UK students only. Funding for overseas fees is not provided.