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A reconfigurable detector for measuring the spatial distribution of radiation dose for applications in the preparation of individual patient treatment plans

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ABSTRACT

In this work, a novel reconfigurable Dose-3D detector intended for a full spatial therapeutic dose measurement to improve radiotherapy treatment planning is presented. The device is composed of a reconfigurable detection phantom allowing patient-centric adjustments to its geometry, a scalable data acquisition system (including hardware, firmware, and low-level software) designed to change with the phantom's configuration seamlessly, and a high-level software package for tumour geometry extraction based on computer tomography scans. Extracted geometry will be used in the Monte Carlo simulations and the configuration of the phantom. Each of the components to be used in the measurement system has been assessed obtaining the following results. The scintillating voxels' light output is sufficient. The data acquisition system with its hardware and software has been tested using artificial testing signals and laser light proving a reliable and robust means of physics data reconstruction.

1. Introduction

3D dosimetry is an important step in the planning and verification of radiation therapy. Currently, full 3D dose measurements are achieved mainly with radiochromic detectors or polymer gels [1]. These, while accurate [2], require external equipment for readout and do not provide real-time information. Descriptions of an active 3D detector for radiation therapy exist [3], but these are dedicated for proton irradiations.

As a solution to the lack of an active detector for X-ray based therapies, we propose a dedicated X-ray detection phantom, composed of scintillator voxels, designed to be reconfigurable in terms of size and spatial arrangement. The phantom's data acquisition (DAQ) system architecture allows straightforward changes to the detector's geometry without loss of detection performance. The hardware will be coupled with a software package (*high-level software*) that allows the extraction of the tumour geometry for use in the Monte Carlo simulations and during the phantom geometry configuration process.

2. Materials and methods

Fig. 1 shows the overview of the project. The detection system (phantom) is built with a reconfigurable array of plastic scintillators, connected by fibre optic cables to a modular DAQ system handled by a low-level scalable software, which uses network connections to individual DAQ modules. The high-level software analyses computer tomography (CT) scans of a particular patient using machine learning (ML) techniques obtaining segmented and classified information about the organs and cancerous regions' placement. This data is used to prepare a patient-specific treatment plan, simulations, and a dose measurement phantom based on the geometries of the tumour and its surroundings.

Dose measurement and reconstruction system. The detection voxels (currently $10 \times 10 \times 10$ mm^3 cubes) can be formed into a phantom using reconfigurable 3D-printed cases, which allow optical isolation between the voxels and from external light sources, as well as the attaching

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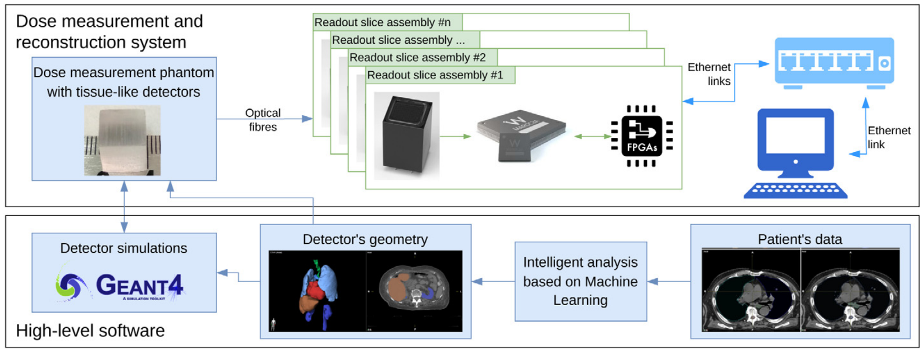

Fig. 1. An overview of the project. Based on software analysis of the CT scans, the geometry of the cancer is found and used for the simulations and the creation of the 3D dose measurement phantom. Detailed description in Section 2.

optical fibres to the scintillators. The opposite side of the optical connection is coupled with a set of multianode photomultiplier tubes (PMT) assemblies with the necessary readout electronics called *slices*.

Each slice is capable of handling up to 64-channels (voxels) using a multianode PMT assembly, a dedicated front-end application-specific integrated circuit (ASIC), and a field-programmable gate array (FPGA). The number of active slices can be changed according to the needs of the detection system with the only limitation being the network connection between the DAQ personal computer (PC) and the electronics. The low-level software is able to handle any number of slices [4] provided that the computing power of the DAQ PC is sufficient.

Given the high intended reconfigurability of the phantom, we opt to use 3D-printed scintillator cubes [5]. 3D-printed samples were compared to a commercially available model — RP-408 in terms of the light output [6]. The PMT and ASIC performance has also been investigated using an artificial charge pulse and a laser light source [7].

High-level software. The very first deep learning model based on Generative Adversarial Networks (GANs) architecture has been built and tested for 3D medical data augmentation purposes [8].

3. Results

Scintillator performance. 3D-printed scintillator cubes proved to have sufficient light output in comparison to the commercial RP-408, i.e. 43.2% for the blue sample and 49.0% for the violet sample [6].

DAQ system. The DAQ system has been a subject of multiple tests. A functional firmware test ensured proper and reliable communication between the FPGA and the front-end ASIC. 1 Gbps Ethernet link used for each slice was proven to be more than sufficient for the data rate of a single ASIC, which produces not more than 55 kEvents/s. The total data rate for the entire phantom has not been measured yet.

Calibration tests of the readout ASIC allowed testing the functionality of the device, as well as gathering preliminary data. Full-chain measurements using a laser light source illuminating the PMT assembly were also performed (with all the components of a single slice in place), recreating 1 kHz laser pulse rate using photon counting mode in the ASIC [7]. After illuminating all the PMT channels, charge measurement data gathered using the DAQ system has been analysed. For ASIC gain set to 1.0, the channels presented a total spread of $\pm 40\%$ of the measured signal's amplitude. Given the range of the gain setting (0–3.984) in the ASIC this can be equalised.

High-level software preparation. The very first augmentation model based on Generative Adversarial Networks (GANs) was built and tested. The loss function values during the process of training oscillated in ranges 10^{-5} – 10^{0} and 10^{0} – 10^{1} for the Discriminator and Generator respectively. The visual results in the form of generated images seem very promising [8].

4. Conclusion

Individual components of the dose measurement system were tested and show good performance. Based on the results collected so far, we can confirm that it is possible to build a detector intended for spatial therapeutic dose reconstruction.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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