Fast regional readout CMOS Image Sensor for dynamic MLC tracking

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Abstract. Advanced radiotherapy techniques such as volumetric modulated arc therapy (VMAT) require verification of the complex beam delivery including tracking of multileaf collimators (MLC) and monitoring the dose rate. This work explores the feasibility of a prototype Complementary metal-oxide semiconductor Image Sensor (CIS) for tracking these complex treatments by utilising fast, region of interest (ROI) read out functionality. An automatic edge tracking algorithm was used to locate the MLC leaves edges moving at various speeds (from a moving triangle field shape) and imaged with various sensor frame rates. The CIS demonstrates successful edge detection of the dynamic MLC motion within accuracy of 1.0 mm. This demonstrates the feasibility of the sensor to verify treatment delivery involving dynamic MLC up to ~400 frames per second (equivalent to the linac pulse rate), which is superior to any current techniques such as using electronic portal imaging devices (EPID). CIS provides the basis to an essential real-time verification tool, useful in accessing accurate delivery of complex high energy radiation to the tumour and ultimately to achieve better cure rates for cancer patients.

1. Introduction

Volumetric modulated arc therapy (VMAT) is an advanced radiotherapy technique which involves arcing the linac around the patient while delivering the radiation beam shaped by dynamic multileaf collimators (MLCs) [1]. VMAT also has variable dose rate (beam fluence rate) and arcing speed during beam delivery. Electronic portal imaging devices (EPIDs) are widely used tool for geometric verification and dose verification of radiotherapy treatment. EPIDs have a large field of view (typically greater than 20 cm x 20 cm) and allow beam’s eye view (BEV) imaging. However the EPID has a frame rate limit of about 12 frames per second and suffers from image artefacts such as ghosting and image lag [2], which limit the ability to monitor a dynamic treatment delivery and result in inaccurate sensor response (i.e., dose measured at a specific irradiation period). An imaging modality with very fast sampling is desirable to monitor the MLC movement as well as changes in the dose rate during VMAT. Otherwise the benefit of these techniques can be degraded due to inability to assess the success of treatment delivery. A few protocols to evaluate VMAT delivery have been published [3, 4] but the evaluation made was of the overall quality of the cumulative dose delivered and did not provide any information regarding the performance of the MLC leaf positions.

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Complementary metal-oxide semiconductor Image Sensors (CISs) have evolved over the past 20 years into a competitive imaging technology due to technology scaling of CMOS and the feasibility of high numbers of pixels integrated on-chip. The sensor allows fast region-of-interest (ROI) read-out which enables the user to trade array size, with read-out speed. CMOS has also recently been successfully made radiation hard [5] and can be fabricated into a large array format using stitching technology [6]. Therefore, this paper discusses a preliminary study of using a prototype Complementary metal-oxide semiconductor Image Sensor (CIS) for tracking dynamic MLCs (DMLCs) by utilising fast, region of interest (ROI) readout functionality. This leads to application of the prototype CIS in VMAT verification which has been recently published [7].

2. Materials and Methods
The CMOS Image Sensor used in this work was developed by the MI-3 consortium (UK) [8]. The sensor comprised 1350 rows × 1350 columns of 40 µm square pixels, giving a sensing area of 54 mm × 54 mm. Sensor frame rate could be increased from ~20 frames per second (f/s) to ~400 f/s by reducing the read out from 1350 rows to 70 rows of pixels in ROI read out mode. The CMOS Data Acquisition System (DAQ) used a Memec Virtex-II Pro 20FF1152 FPGA development board (Xilinx, Inc., San Jose, CA, USA). The host PC controls the CIS through the FPGA board via a dynamic link library where the operation of the sensor can be customised. The binary image data is transferred back to the PC at GBit speeds and analysed offline using Matlab (MathWorks, Natick, MA, USA).

Assessment of DMLC leaf tracking success in the presence of variations in frame rate from ROI (which affect the visibility of the moving MLC) was performed by imaging a DMLC sequence designed to employ various leaf speeds. The work was carried on an Elekta Synergy accelerator (Elekta, Crawley, UK) with a Beam Modulator head, using 6 MV photon beam. The sensor was placed away from the radiation beam and was optically coupled in camera configuration with a fast terbium doped gadolinium-oxy-sulfide Gd$_2$O$_2$S:Tb scintillation screen.

The design of the DMLC sequence is shown in Figure 1. The triangular configuration means that the leaves will have to travel at different speeds to ensure all MLCs close in at the end of the delivery. A series of images of the MLC moving across the field was acquired at frame rate 21.0 f/s, 50.4 f/s, 100.9 f/s, 201.6 f/s and 403.6 f/s. Because different frame rates were achieved by reducing the number of rows through ROI read out, the sensor FOV decrease with increasing frame rate as shown in Figure 1. The middle row of imaging area was positioned on the middle leaves of the prescription to make sure all ROIs used, imaged the fastest MLC leaves in the middle.

The leaf edge in the images was located with an automatic edge tracking algorithm shown in Figure 2. The coordinates of the MLC edges on the image were located along the profile plot for the right edges where the MLC leaves were moving. The detection was repeated row-by-row across the triangular field for all frames acquired. The position of the MLC leaves on the captured images was compared with the expected position from the prescription.

3. Results and Discussion
The edges tracked from the triangle field are presented for every 0.1 s time interval in Figure 3 for the central four MLC leaves (MLC number 18 to 21) at frame rates 201.6 f/s and for the central two MLC leaves (MLC number 19 and 20) at 403.6 f/s. The leaves are moving from right to left in the shown orientation for prescribed positions between 15 mm to -25 mm. The smoothing of the jagged shape of the MLC leaves is due to light scattering before reaching the camera in the indirect detection geometry [9]. Most of the edges tracked have a smooth line except for some edges where the lines are noisier. Examining the corresponding images reveals these are due to spiking pixels characterised in [6] which periodically affects certain pixel columns in the prototype CIS.

To exclude the edge smoothing of the tracked MLC, mean pixel value from the region within the middle of each leaf is selected as the leaf position. Edge detected across each leaf is divided into three bins. The middle bin is selected as the MLC position to exclude the smoothed regions. The edge position was calculated for MLC number 19 (the fastest MLC speed) across MLC position of 5 mm to -25 mm, i.e., the range shown in Figure 3. Position error is defined as the difference between the tracked position and the prescribed positions. The existence of spiking pixel in the data and the variation of sensor frame rates has not caused the sensor tracking accuracy to be worse than 1.0 mm. This is better than the 3 mm maximum error set by the AAPM [10]. The smoothing of the MLC
leaves’ edge tracked due to light scattering from the sensor in camera configuration has not interfered with the accuracy of the tracked MLC leaves positions.

Figure 1: Imaging area for each frame rate used to image the moving triangular field overlaid on the prescription.

Figure 2: Flowchart of the automatic edge tracking method used to detect MLC edges from acquired CIS images.

Figure 3: Plot of leaf edge detected for the central four MLCs (MLC number 18 to 21) at frame rates 201.6 f/s and for the central two MLCs (MLC number 19 and 20) at 403.6 f/s. The colour of each leaf edge tracked is shown alternating between different colours at every 0.1 s time interval, moving from right to left.

It has been demonstrated that the prototype CIS is able to track MLCs at a high sampling rate throughout the DMLC delivery. The use of fast ROI read out shows CIS is much faster than currently available alternatives, such as EPIDs. ROI read out, allows the frame rate to increase to ~404 fps using 70 rows regional readout (20 times increase from a full frame readout). Moreover, by using a combination of ROI sizes, speeds and positions, a sequence of ROI read out that changes its size and position across the full frame can be used to selectively image different groups of dynamically moving...
MLCs. Imaging only the smaller ROI with the sensor also reduces the image processing workload and allows real-time verification of the MLCs. This has great potentials in commissioning a new treatment technique involving DMLC delivery, where independent assessment of the MLC leaves can be investigated by tracking the leaves’ positions across the delivery.

A recent study using this sensor for VMAT verification [7] has demonstrated the novel capability of this sensor for verification of not only dynamic MLC leaves position, but also dose rate at very high frame rate. The MI-3 Plus consortium has recently developed a wafer size CMOS image sensor [11], constructed using the same stitching technique used for the prototype CIS in this study but across the whole wafer. The CIS has a total imaging area of 12.8 cm × 12.8 cm with two sides buttable, which can be doubled to 25.6 cm × 25.6 cm by joining two by two sensors together. The large imaging area is comparable to the size achieved by an EPID, but at the same time has a faster frame rate which is limited in an EPID. The wafer size CIS is expected to allow BEV imaging in direct detection geometry, which eliminates the light scattering problem from camera geometry observed in this work.

4. Conclusion
The use of ROI read out demonstrated that the prototype CMOS Image Sensor is faster and more versatile than currently available alternatives such as EPID. CIS provides the basis to an essential real-time verification tool, useful in accessing accurate delivery of complex high energy radiation in complex radiotherapy delivery such as VMAT.

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