Miniature C-arm Simulator Using Wireless Accelerometer Based Tracking

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1 Purpose

The C-arm has enabled minimally-invasive procedures to be performed under fluoroscopic-guidance (static or real-time images). The downside to these procedures is that the clinician and patient are both subject to an exposure of radiation proportional to the amount of time the X-ray is "on". Radio-opaque contrast is often injected into the patient to provide confirmation of instrument placement or improve identification of anatomical regions (eg. Aortic Root). This contrast may also be harmful to the patient [1]. Therefore, developing training and planning systems for minimizing the time spent "fluoro-hunting" is a major challenge with these procedures, as is limiting the need for contrast.

Current solutions allow the clinician and trainees to practice C-arm manipulation and image acquisition without the use of radiation by generating a Digitally Reconstructed Radiograph (DRR) based on a pre-operative CT scan of the patient and the position of the C-arm head (X-ray source) relative to the patient. Stephan et al. [4] obtain the position of the C-arm via optical tracking. While this provides a highly accurate C-arm position, it greatly limits the range of motion as the optical tracker must have a clear line-of-sight (LOS) of the C-arm head in order to track its position. Furthermore, optical trackers are often too expensive to make such simulators easily affordable. De Silva et al. [3] use the C-arm motor encoding's for tracking which eliminates any LOS issues but restricts the training to operative C-arms.

The proposed solution uses a 3D printed 10:1 scale C-arm model, wireless accelerometers and custom software to integrate this with a DRR derived from a CT-based model. It offers the benefits of training on a physical C-arm while remaining cost-effective, portable, and inexpensive. Accelerometers are highly accurate for tracking the orbital and angular positions of a C-arm head [5], they are much cheaper than optical trackers and eliminate any LOS issues.

2   Methods

The physical components were designed in Spaceclaim [4] and then 3D-printed using PLA plastic on an Ultimaker3 3D printer. Three 9-axis WitMotion JY901BT Bluetooth accelerometers were then fixed onto the C-arm. One accelerometer was attached to the detector portion which enabled tracking of the C-arm head by applying a 180°transform. The orbital and angular rotational DoF's tracked by this accelerometer were enabled by a mechanical turntable which provided rotation about the X-axis (axis perpendicular to spine phantom and "up" vector), and a set of rollers attached to this mechanism which allowed the "C" portion to rotate freely about the Y-axis (axis parallel to spine phantom). A second accelerometer was attached to a handle that could be rotated to provide one translational DoF motion of the OR table. The angle reported from the accelerometer was converted into translational movement based on the gear ratio. The third rotational degree of freedom was enabled by a second mechanical turntable mechanism attached to the table, which was tracked by the third accelerometer. The WitMotion Accelerometer was added as a new device to Plus Toolkit [5] which enabled easy integration with 3DSlicer [6] and Visualization Tool Kit (VTK) [7]. The data was acquired via a one-way serial port bluetooth connection. The system is shown in Fig. 1.

The data from the accelerometers was used in order to position the camera in the VTK volume rendering coordinate space. The CT volume was rendered using a GPU ray tracing algorithm and a 1-dimensional color and opacity transfer function (derived experimentally) that simulated the attenuation of X-rays in tissue. This enabled the generation of real-time DRR's [2].

For the application of the C-arm simulator, two procedures were focused on: Lumbar Spine Epidural Injections and Transcatheter Aortic Valve Replacement Procedures. For the latter a custom algorithm was developed to simulate the injection of a contrast agent into the aortic root. A heart CT volume was segmented to produce a labelmap volume with a geometry identical to the original CT volume but with each voxel containing a label corresponding to its anatomical region instead of an actual intensity value. Using this labelmap, the voxels in the heart CT data corresponding to the aortic root had their intensity values automatically increased to a fixed threshold to highlight greater contrast between the aortic root and the surrounding heart muscles. This algorithm was developed to fit into the workflow of patient-specific heart modelling.
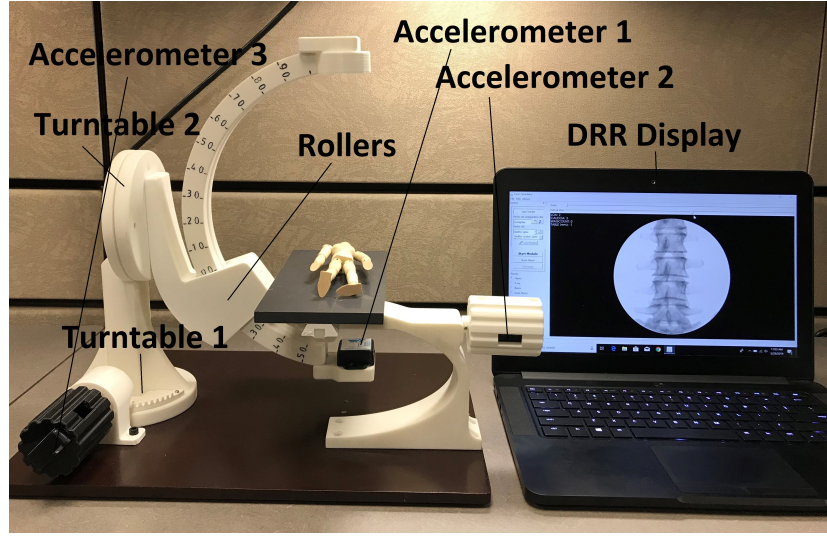
3   Results

Qualitative analysis shows that the system can generate accurate real time DRR's based on the position of the tracked C-arm head. A user study is being

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[4] http://www.spaceclaim.com/en/default.aspx

[5] https://plustoolkit.github.io/

[6] http://slicer.org

[7] https://vtk.org/

Fig. 1. The entire system. Accelerometer 1 used for the tracking of the orbital and angular DoF's enabled by Turntable 1 and the rollers(hidden from view), accelerometer 2 used for tracking of the translational DoF of the table, accelerometer 3 used for the tracking of Turntable 2, real-time DRR display updated via serial port bluetooth connection.

conducted to evaluate the system as a training tool. The 3D-printed C-arm and top views of the spine DRR, non-contrast enhanced heart DRR, and contrast-enhanced heart DRR are shown in Fig. 2.
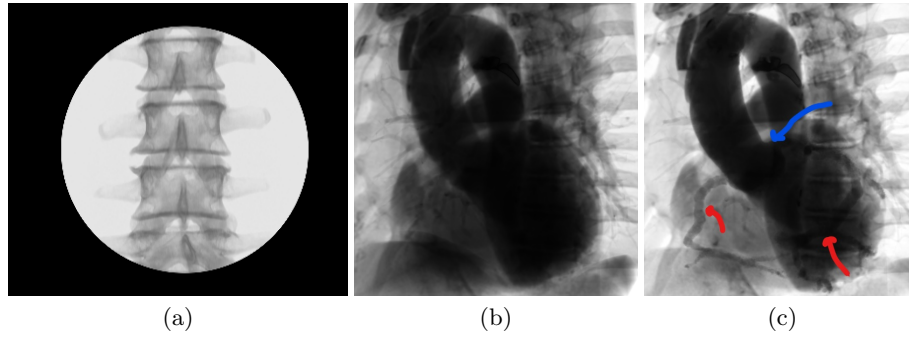
Fig. 2. (a) Spine DRR (b) Heart DRR (c) Heart DRR (contrast-enhanced, blue arrow points to aortic root, red arrows point to coronary arteries)

4   Conclusions

A portable, wireless, and inexpensive C-arm training simulator has been developed. Qualitative analysis shows that the system can generate real-time DRR's based on the position of the C-arm head. A custom contrast enhancement algorithm has been developed to simulate the effects of contrast dye flowing through the aortic root and coronary arteries of the heart. Quantitative analysis of the accuracy of the DRR's as well as experiments validating the effectiveness of the system as a training tool have yet to be performed.

Once acceptable results have been achieved in terms of the accuracy of the DRR's produced, the system will then be evaluated by conducting a randomized control trial, in which half the subjects will perform standard training with prior use of the proposed C-arm training system and half without. These results will then be analyzed to quantify the effectiveness of the proposed system as a training tool.

Preliminary work has been done to incorporate the tracking of a needle into the DRR's in order to allow end-to-end simulation for C-arm procedures. Keeping in line with the cost-effective and portable model, experimentation with the use of webcam tracking technology has been evaluated. Initial results have shown good potential and it is suspected that the incorporation of the needle will be integrated into the system as further research improves the underlying webcam tracking technology.

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