Development and Evaluation of an Open-Source Virtual Reality C-Arm Simulator

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ABSTRACT
C-Arm positioning for interventional spine procedures is often associated with a steep learning curve. This task requires mentally reconstructing 3D surgical tools and patient anatomy from a 2D X-ray image, which is non-trivial and usually acquired through years of experience. Furthermore, standard training via apprenticeship-based programs must be limited due to the unnecessary exposure to ionizing radiation. To this end, we propose a radiation-free, Virtual Reality C-Arm simulator for interventional spine procedure training. **Methods** We implemented the simulator as an open-source module in 3D Slicer, and evaluated its efficacy as a training tool through a user study, recruiting medical residents and expert clinicians. The evaluation consisted of two rounds of C-Arm placement tasks in the simulator, in which the user aimed to achieve the optimal X-ray projection, for three standard views commonly employed in spinal procedures. The training component took place in between evaluation rounds, with each user completing a standardized tutorial and practice session in the simulator. **Results** After completing the training component, the users showed an overall significant improvement in C-Arm placement capabilities with regards to angular accuracy (mean $\approx 2^\circ$ improvement), and total procedure time (mean $\approx$ 11 minutes less time). The users also acquired on average $\approx$ 16 fewer virtual X-ray images, however this change was not significant. The face and content validity was evaluated positively through a Likert scale questionnaire, with a mean score of 4 (out of 5) or higher for each of the questions. **Conclusions** We have built an open-source VR C-Arm simulator and evaluated its efficacy as a training tool for C-Arm placement in fluoroscopy-guided interventional spine procedures. The quantitative results show the simulator provides effective training for C-Arm positioning, while eliminating the exposure to ionizing radiation associated with the current training standard. Although this work is catered towards spinal procedures, the system is extendable to other fields, such as cardiac and orthopaedic, and will be explored in future works.

KEYWORDS
Virtual Reality; C-Arm; Simulator; Surgical Training; Digitally Reconstructed Radiograph; Head-mounted Display; SlicerVR.

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1. Introduction

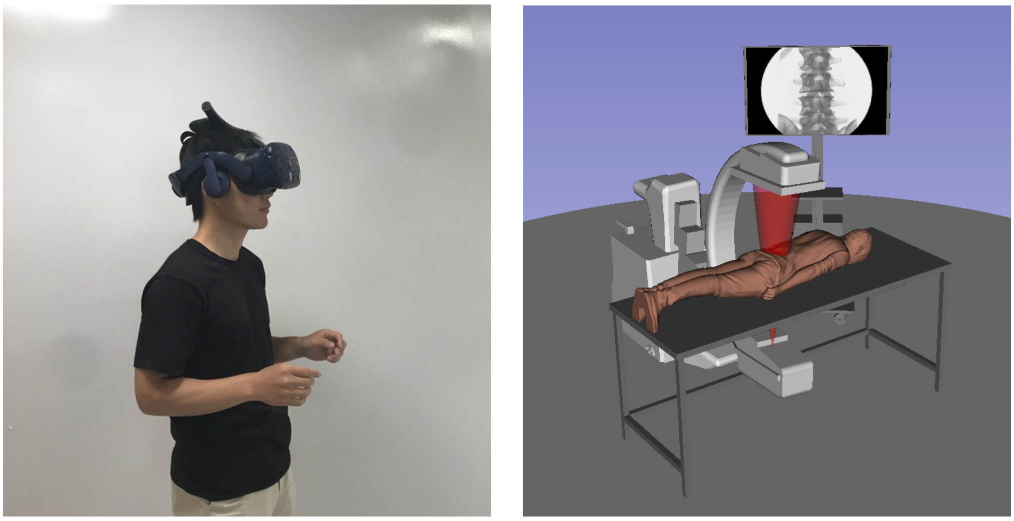
C-Arm fluoroscopy is ubiquitous in interventional spinal procedures due to its real-time nature, versatility, moderate cost, and the ability to depict both the surgical target (eg. osseous structure) and surgical instrument (eg. a needle) simultaneously. Common spinal needling procedures performed under fluoroscopy guidance include epidural(Wagner 2004) and facet joint injections(Peh 2011). In these procedures, continuous or intermittent fluoroscopy is used to i) provide adequate visualization of the anatomy, ii) to guide the insertion of the needle, and iii) to confirm the final position of the needle tip. This leads to an increase in ionizing radiation exposure to both the patient and clinical staff(Zhou et al. 2005). Adequate image guidance and visualization is achieved through manipulation of the C-Arm pose (orientation and position) relative to patient anatomy, requiring both skill of the operator and additional fluoroscopic imaging.

The amount of radiation exposure to surgeons and patients is correlated with the skill and experience of the surgeon(Blattert et al. 2004). One approach to controlling radiation exposure is to optimize the training of operating room personnel who use C-Arm systems, so as to reduce the time and radiation needed to obtain a specific image or monitor a surgical procedure(Bott et al. 2011). Touchette(Touchette 2017) implemented a physical simulator, comprising a clinical C-Arm and a mannequin, whose pose was tracked using an optical tracking system and used to generate a digitally reconstructed radiograph (DRR) from a 3D CT scan(Sherouse et al. 1990). In the context of pelvic trauma imaging, Touchette reported a 53% decrease in scout images acquired when aligning radiographic images and a 10% increase in accuracy when the final images were taken. The use of a clinical C-Arm and optical tracking system limits its accessibility and incurs additional costs.

(Bott et al. 2011) proposed a virtual-reality (VR) based simulator, consisting of a series of computer-based imaging exercises in which C-Arm operation for various surgical procedures is simulated by the trainee. This VR environment is visualized on a traditional 2D monitor display and interaction is achieved via a keyboard and mouse, with a DRR being used to provide real-time visual feedback. While their system is not specific for spinal intervention, they provided evidence of a positive short-term effect of simulation-based training in radiology, although the long-term effects of such training on knowledge internalization are as yet unknown. This system was further developed to incorporate the use of a head-mounted display (HMD), allowing the user to receive training of C-Arm manipulation in an immersive environment(Süncksen et al. 2018). This system was widely appreciated by non-medical participants, although no quantitative results were reported. Their system also lacks the ability to track a surgical needle in physical space.

Building on the work from(Allen et al. 2020), we propose an immersive VR system for the training of C-Arm manipulation (Fig. 1). Our system is similar to(Süncksen et al. 2018) but tailored for fluoroscopy-guided spinal intervention and implemented as an open-source scripted python module in 3DSlicer (Slicer)[1]. While the purpose of this paper is to demonstrate the system's utility in training the operator for the selection of the appropriate views for intervention, when combined with an external tracking device(Groves et al. 2019), it also has the ability to track a surgical needle in physical space.

[1]https://www.slicer.org/



(a) (b)

Figure 1. (a) A user wearing the VIVE Pro HMD using the proposed system. (b) A screenshot of the virtual scene from the user's perspective.

2. Methods

2.1. System Architecture

In the context of VR simulators for medical applications, Unity[2] as the underlying platform enables excellent built-in support for C-Arm interaction using the VR controllers, as demonstrated in (Süncksen et al. 2018). Slicer, while limited in its support for VR interaction, offers clear advantages in terms of integration with medical research modules, which permit greater extendability of the application. In practice, the clinician interacts with the C-Arm not physically but via verbal instruction to the Medical Radiation Technologist (MRT), who then physically manipulates the C-Arm. The choice of Slicer over Unity as the underlying VR platform for our system is justified by i) the lack of physical interaction required from the clinician, and ii) the medical research modules that can be integrated into the system for future iterations. A high-level system architecture overview is shown in Fig. 2. The SlicerVirtualReality(Choueib et al. 2019) (SlicerVR) extension exposes the transforms for the HMD, controllers, and any generic trackers associated with the HMD which integrates seamlessly with other Slicer modules.

2.2. System Requirements and Hardware

The hardware requirements are dictated by the computational resources needed to drive the HMD system. In our configuration, we employed a Windows 10 Pro computer equipped with a 3.2 GHz Intel Core i7-8700 CPU with 32 GB of RAM. An HTC VIVE Pro HMD was used for the development and testing of the system. As well as the HMD device, The VIVE Pro hand controllers were configured to control the C-Arm and a generic tracking device was used to anchor the VR scene.

[2]https://unity.com/

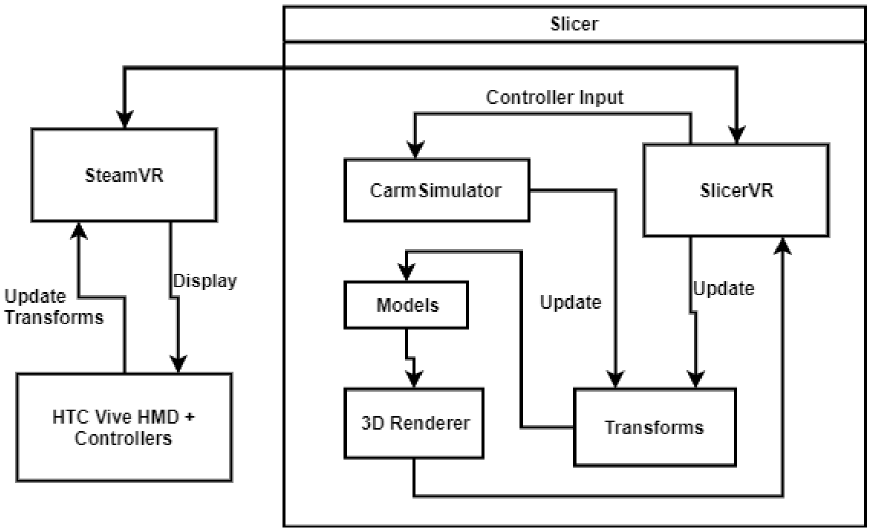


Figure 2. System Architecture. How the proposed module communicates with other Slicer modules to control the logic for DRR generation and virtual C-Arm kinematics.

2.3. Virtual C-Arm

In order to enable the rotational DoF's of the C-Arm, we extracted the gantry, cranial/caudal support (CC support), and wag support components (see Fig. 3) using SpaceClaim [3] from a 3D model of a C-Arm taken from TurboSquid [4]. The surface representation of these support components were imported into Slicer.

2.4. DRR Generation

The DRRs were generated based on a patient CT and the pose of the virtual C-Arm. The pose of the C-Arm $\mathrm{T}_{\mathrm{Source}}$ was calculated based on a similar method to (Allen et al. 2020). The volume was placed at the C-Arm isocenter and the pose was calculated as follows:

$$T_{Source} = T_{Rad}T_{Gantry}T_{CC}T_{Wag}T^{O}_{Table} \quad (1)$$
$$T_{Wag} = -T^{O}_{W}T_{Z}T^{O}_{W} \quad (2)$$

where $\mathrm{T}_{\mathrm{Rad}}$ is defined by the translation matrix based on the radius of the C-Arm, T_{Gantry} and T_{CC} are defined by the rotation matrices obtained from the Gantry and CC support rotations respectively. T^{O}_{Table} is the matrix defining the table's translation along the Y axis, T^{O}_{W} the translation of the Wag axis from the origin, and T_Z is the rotation matrix obtained from the Z rotation of the entire C-Arm about the wag axis. The transformation chain used to model the kinematics of the C-Arm in the Slicer scene can be obtained by downloading the source code[5] of the module.

We used the calculated T_{Source} pose to position the virtual X-ray source, focal point, and up vector in the DRR generation coordinate space. We chose to render

[3]http://www.spaceclaim.com/en/default.aspx
[4]https://www.turbosquid.com/
[5]Source Code will be released upon publication of the paper

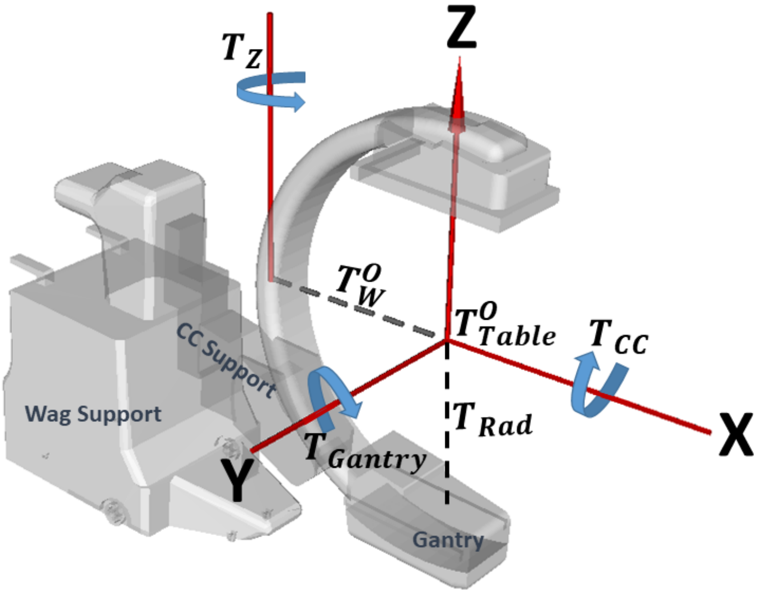


Figure 3. The C-Arm components (gantry, cranial/caudal support, and wag support), and the transforms required to calculate the position of the C-Arm source.

the DRRs using a ray-tracing approach with an expert clinician designing a custom 1-D transfer function mapping CT Houndsfield Units to Opacity values. Because the volume rendering is hardware-accelerated in Slicer, real-time DRR's may be generated based on the dynamic pose of the virtual C-Arm.

2.5. User Study

For the evaluation of the system, we performed a single-center user study approved by the Health Sciences Review Ethics Board of our local institution. We recruited 12 anesthesiology and orthopaedic residents and 2 expert users (one Anesthesiologist and one Interventional Radiologist) to participate in the study. While a few of the residents had some experience observing C-Arm procedures, none had any practical experience performing them. We conducted an evaluation task in which the residents were required to manipulate the C-Arm to obtain 3 standard fluoroscopic views commonly employed in interventional spine procedures: Full AP (Anterior-Posterior), Full Lateral, and Scotty Dog ($\approx$ 20 lateral). Manipulation of the C-Arm was performed by the study administrator via verbal instruction from the user. This was to ensure the setup best simulated a typical clinical scenario, with the study administrator mimicking the role of a Medical Radiation Technologist. The ground truth angles for these views (Fig. 4) were set by an expert clinician with more than 20 years of experience in pain management procedures. Each user performed the evaluation twice, with a 7 minute period to train on the system using the real-time DRR functionality in between rounds. For the training component, a spine CT of a healthy patient was used to teach the users on how to acquire the optimal projection for each view. However, for the eval-

(a) (b) (c)

Figure 4. The three standard fluoroscopic views. Full AP (a), Full Lateral (b), and Left Scotty Dog (c) with Scotty Dog outlined.

uation component, we used a scoliotic spine CT instead. This ensured that in order to perform well in the evaluation, users were required to understand the intricacies of how the 2D X-ray image reflects the 3D position of the C-Arm with respect to the patient, and were not simply memorizing the steps to take to achieve the optimal projection. The same spine CT was used for both rounds to ensure differences in pathology did not influence the difficulty of the task. The volume was also randomly rotated and/or shifted between rounds to avoid memorization of the C-Arm parameters. After the evaluation, each user filled out a standard 5-point Likert scale questionnaire to assess the face and content validity of the system (Barsom et al. 2016; Mu et al. 2020).

2.6. Performance Metrics

To evaluate the performance of the participants, the following metrics were recorded: i) total procedural time, ii) angular and translation accuracy as compared to the gold standard set forth by the expert clinician, and iii) number of virtual fluoroscopic shots as a surrogate for the total x-ray exposure.

3. Results

3.1. User Study

Using the hardware specified in Sec. 2.2, the system runs at a frame rate of 90 hertz with negligible latency. The novice user performance results are shown in Figure 5. The angular and translation errors are reported by comparing the final pose of the C-Arm to those defined by the clinical expert for the specified view. Outliers were removed, which were defined as values falling outside of three scaled median absolute deviations away from the median, and then a paired T-test was used to analyze the significance in change for any of the metrics between rounds. The overall performance for each user improved after completing the training portion of the study, with a significant improvement in at least one of the metrics for all three views. The average number of virtual fluoroscopic shots decreased from 42.33 ± 21.29 to 26 ± 13.27 ($p \geq 0.05$) and the average procedure time decreased from 20.71 ± 5.43 min to 9.72 ± 4.38 min ($p < 0.05$). The overall feedback of the system was positive with the Likert scale questionnaire results shown in Tab. 1.

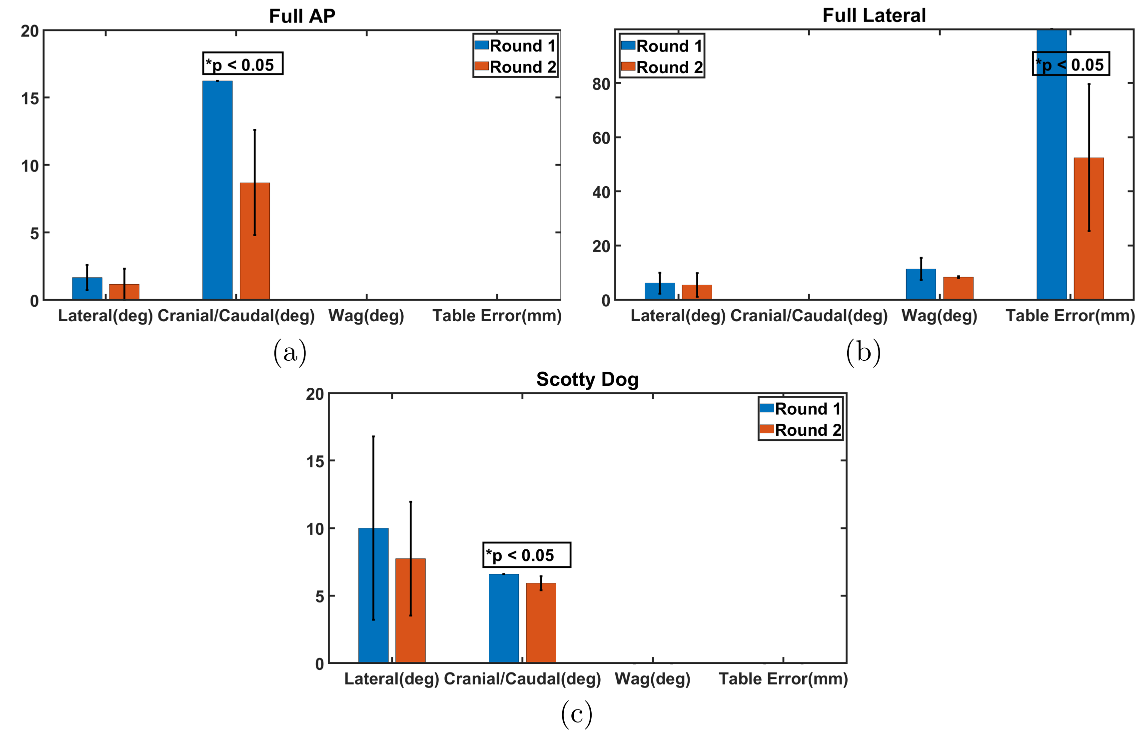


Figure 5. Novice user results for the evaluation component of the study. Significant improvement was shown for each view. The y-axis unit corresponds to the unit shown in brackets for each individual x-axis value.

Face Validity (n = 14 (12 novices, 2 experts))	**Mean**	**Min**	**Max**
The simulator realistically represents an X-ray image	4.6 ± 0.5	4	5
The X-ray image is representative of the virtual C-Arm and patient position	4.6 ± 0.6	3	5
Interaction with the C-Arm in the VR environment was user friendly	4.3 ± 0.9	2	5
Integration of simulator into medical education would be useful	4.7 ± 0.6	3	5
Your spatial understanding of the movement of the C-Arm in VR was more intuitive than on a 2D display	4.5 ± 0.6	3	5
Content Validity (n = 2 experts)			
The simulator is suitable for training novices	5.0 ± 0.0	5	5
The simulator is suitable for training experts	5.0 ± 0.0	5	5

Table 1. Questionnaire results (1 = Strongly Disagree, 2 = Disagree, 3 = Neutral, 4 = Agree, 5 = Strongly Agree).

4. Discussion

To the authors' knowledge, this is the first presentation of an open-source VR C-Arm simulator demonstrating quantifiable results on its efficacy as a training tool for medical residents. The simulator has the potential to replace traditional C-Arm training, allowing the user to train outside of the fluoroscopy suite, without the time constraints and exposure to ionizing radiation.

The proposed system is the first iteration in what will eventually be an end-to-end fluoroscopy suite simulator. Through the PLUS Server(Lasso et al. 2014) and SlicerIGT(Ungi et al. 2016), we can integrate tracked surgical tools into the environment. Once the participants are trained adequately in C-Arm positioning, they will transition into surgical intervention tasks such as spine needle insertions. To further enhance realism, we plan to incorporate a physical spine model(McLeod et al. 2015) and external spatial tracking system(Groves et al. 2019). This will allow the user to insert a tracked needle into a physical spine, while getting both tactile and visual (2D DRR and 3D VR) feedback. The DRR generation will incorporate the real-time positioning of the needle.

5. Conclusion

We have developed an open-source VR C-Arm simulator for interventional spine procedure training. To evaluate the efficacy of our proposed platform, we conducted a user study consisting of a training component and evaluation task. The purpose of the study was two-fold: i) to gain feedback on the VR system to improve the immersion and usability, and ii) to quantify the efficacy of our system as a training tool. The results indicate that our simulator provides adequate training for C-Arm placement skills, while eliminating the accompanying radiation hazard associated with the current standard of training. With the ability to use the system outside of the OR in a non-medical environment, the user is not constrained to a fixed allotment of training time. Valuable feedback was achieved via evaluation of the face and content validity, which serves as the foundation for the direction the next iteration of the system will take.

Compliance with ethical standards

Conflict of interest

The authors declare that they have no conflict of interest.

Ethical approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

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