Interactive Digital Twins for Simulating the Future of Work in AI- and Robot-assisted Operating Rooms

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Like many arenas in the modern workplace, the operating room is undergoing rapid changes due to human-in-the-loop AI and robotic systems. These will likely disrupt existing workflows and introduce new routines for setup, calibration, and execution, but they have enormous potential to benefit patient outcomes, improve OR efficiency, mitigate occupational risk, and broaden access to the highest standard-of-care. In order that such technologies are adopted as quickly as possible, surgeons and stakeholders must be confident in their use, compared to longstanding practice with which they are overwhelmingly more familiar, so as to deploy them to patients for whom they are ultimately responsible [3]. Further complicating this issue is the fact that a surgery may occur infrequently and newly acquired systems can alter procedures all of a sudden, limiting the ability to learn on the job. To ready individuals for the future of work in their operating room and to facilitate knowledge retention, there is a need for repeatable, freely-available training curricula that reflect the capabilities and constraints of specific ORs. *My goal is to develop interactive digital twin operating rooms and investigate their effectiveness as a knowledge acquisition and retention tool for complex workflows associated with human-in-the-loop AI and robotic surgical systems.*

This proposal aims to combines the advantages of interactive computer simulation for surgical training with the dynamic realism of a digital twin. A digital twin is a virtual representation of a real object, like an operating room or patient, that replicates relevant characteristics such as appearance, dynamics, and physical interactions [1]. In the context of training for complex workflows, which may last several hours, we propose to develop replayable, interactive digital twins of entire operating rooms *over the duration of the workflow*. This would enable a trainee to step into their role in the OR either as a passive observer or an active participant working in collaboration with the AI and robotic systems as well as virtual coworkers. In this "interactive playback mode," the components of the computer simulation that depend on the trainee's chosen role become fully interactive, while other roles and components replicate the recorded workflow.

To investigate the value of such a system, I will develop and evaluate a curriculum for an exemplary surgical workflow with AI and robotic components. Leveraging prior work in AI assistance systems for percutaneous fracture fixation [5], I will work in collaboration with an attending surgeon in Johns Hopkins Department of Orthopedic Surgery to

Figure 1: In preparation this research, I have led the development of a virtual reality simulation for intra-operative X-ray imaging. This room-scale simulation allows users to gain experience at acquiring X-ray images, positioning instruments, and carrying out complex surgical workflows.

develop a workflow for a technician in robot-assisted orthopedic surgery. Training curricula will focus on the role of the radiological technician, who is currently responsible for repositioning C-arm X-ray devices. This role may undergo rapid changes in the coming years with the advent of smart C-arms [4], and so the workflow for OR technicians will expand to cover AI and robotic assistance systems. These steps will take place in three phases over the duration of the fellowship, as outlined below.

Timeline and Objectives

Phase 1: Develop a digital twin OR (July - October 2023). The first phase of research will involve the creation of a platform for digital twin ORs with support for workflow timeseries. In this phase, I will use the Mock Operating Room (MockOR) at the Laboratory for Computational Sensing and Robotics (LCSR) at Johns Hopkins University as the basis for the digital twin. The MockOR is equipped with surgical devices for research purposes, including a fully robotic X-ray device,[1] hand-over-hand positioning robot,[2] and optical tracking systems, which enable the exemplary pelvic trauma workflow. To record a complete digital twin workflow, relevant data include 3D room and instrument models, robot kinematic data, calibrated instrument poses, and human pose information. The OR model may be obtained by reconstructing mesh models based on commercial RGB-D cameras[3] or Neural Radiance Fields [6]. Instrument models may be obtained by segmenting CT scans or by using 3D modeling software [2]. Robot kinematic data is available from research agreements with Brainlab (pending) and Galen Robotics. As a starting point, I have led the development of a virtual reality environment for building skills in conventional percutaneous fracture fixation, including X-ray imaging and tool placement components, shown in Fig. 1.

Phase 2: Create an interactive digital twin for robot-assisted fracture fixation (November 2023 - February 2024). In concert with an attending physician, radiological technicians, and other stakeholders, I will develop a novel workflow for a technician which requires new skills like registering the imaging device with the patient, calibrating robot attachments, and establishing navigational guidance. Ongoing projects which I am leading, including an integrated system for 2D/3D registration in the MockOR, will enable this workflow to rely on AI-driven intelligent surgical systems. Crucially, the envisioned workflow will require a technician to smoothly integrate information from disparate systems, as opposed to traditional workflows for a radiological technician, which involve only a single system, the C-arm. The outcome of this phase will be an interactive recording of the envisioned workflow in the digital twin MockOR, in which the trainee technician will acquire the skills to confidently integrate multiple AI and robotic assistance systems in a complex workflow.

Phase 3: Investigate the effectiveness of workflow curricula (March - June 2024). I will investigate the effectiveness of "interactive playback mode" in the digital twin MockOR with a human subject study consisting of two groups. Group A will receive conventional in-person training from an investigator. Group B will experience training in the proposed digital twin MockOR. Both groups will then be asked to carry out the workflow in the physical MockOR under observation. The observing investigators will not be aware which training the subjects received. The primary outcome variable will be

[1] https://www.brainlab.com/surgery-products/overview-platform-products/robotic-intraoperative-mobile-cbct/.

[2] https://www.galenrobotics.com/about-galen-robotics/.

[3] https://www.stereolabs.com/zed-x/.

Table 1: Budget

		Item	Unit Cost (USD)	Total Cost (USD)	Acquired
Phase 1					
	3D Modeling	Software	100	100	✓
		Assets	10 - 50	500	
	Equipment	3D Camera	600	600	
		PC	5,000	5,000	✓
Phase 2					
	Equipment	Head-mounted display	2,000	2,000	✓
		Hardware	1,000	1,000	
Phase 3					
	Compensation	$n = 20$ participants	40	800	
			Acquired	-7,100	
			Total	3,900	
			Total * 1.5	5,850	

subjects' response to the question, "Overall, how confident are you that you completed the task successfully?" with 1 being "Not at all confident" and 7 being "Extremely confident." Secondary outcome variables will measure successful achievement of intermediate tasks during the workflow. For this study, we will recruit at least 20 participants with a comparable background to radiological technicians. Using Student's t-test, we expect our study to achieve a power of 0.8, assuming a medium effect size.

Budget

Support from The Link Foundation will enable a year-long commitment to development of a robust surgical simulator for image-guided procedures, covering my stipend so that the proposed work can be completed without interference from TA duties. Table 1 outlines the expected budget, not including items that are institutional resources such as the fully robotic X-ray device installed in the Johns Hopkins MockOR and the hand-over-hand surgical robot. We anticipate shipping, taxes, and unexpected costs to total not more than 1.5 times the planned cost. Certain items, including a head-mounted display and PC workstation have already been acquired. Certain unmet dependencies, including a 3D camera to facilitate creation of interactive recordings, will need to be purchased. The project budget for unmet dependencies, including a factor of 1.5, is $5,850. Discretionary lab funds for this amount have been approved by the PI.

References

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[2] Blender Online Community. *Blender - a 3D modelling and rendering package*. Blender Foundation, Stichting Blender Foundation, Amsterdam, 2018. URL http://www.blender.org.

[3] Sanjeev Kaul et al. Da Vinci-Assisted Robotic Partial Nephrectomy: Technique and Results at a Mean of 15 Months of Follow-Up. *Eur. Urol.*, 51(1):186–192, January 2007. ISSN 0302-2838. doi: 10.1016/j.eururo.2006.06.002.

[4] Lisa Kausch et al. C-Arm Positioning for Spinal Standard Projections in Different Intra-operative Settings. In *Medical Image Computing and Computer Assisted Intervention – MICCAI 2021*, pages 352–362. Springer, Cham, Switzerland, Sep 2021. ISBN 978-3-030-87201-4. doi: 10.1007/978-3-030-87202-1_34.

[5] Benjamin D. Killeen et al. An Autonomous X-ray Image Acquisition and Interpretation System for Assisting Percutaneous Pelvic Fracture Fixation. *To appear: Int. J. CARS*, June 2023. ISSN 1861-6429.

[6] Matthew Tancik et al. Nerfstudio: A modular framework for neural radiance field development. *arXiv preprint arXiv:2302.04264*, 2023.