Eva Currle*, Johannes Hemm, Armin Schäfer, Philipp Beckerle, Johannes Horsch, Jan Stallkamp and Markus Kühne

Towards a companion system for collision avoidance during robot-assisted needle placement

Abstract: Robotic assistance systems for surgery enable fast and precise interventions with reduced complication rates. However, these benefits are accompanied by a more complex operating room (OR) and the risk of collision with robotic assistance systems. Current strategies for collision avoidance and minimizing possible injuries require the adaptation of robotic trajectories and a computational model of the surroundings. In contrast, this work presents a novel companion system for collision avoidance without influencing robotic trajectories. The companion system consists of a preoperative planning application and an augmented reality application for intraoperative support. The companion system visualizes the workflow within the OR and allows robot movements to be seen virtually, before they are executed by the actual robotic assistance system. Preliminary experiments with users imply that the companion system leads to a positive user experience, enables users to follow a predefined workflow in the OR, but requires further refinement to improve accuracy for practical collision avoidance.

Keywords: robot-assisted surgery, collision avoidance, augmented reality, companion system, hybrid OR.

https://doi.org/10.1515/cdbme-2021-1027

***Corresponding author: Eva Currle:** Fraunhofer IPA, Project Group for Automation in Medicine and Biotechnology, Mannheim, Germany, e-mail: eva.currle@ipa.fraunhofer.de
Johannes Hemm, Armin Schäfer and Johannes Horsch: Fraunhofer IPA, Project Group for Automation in Medicine and Biotechnology, Mannheim, Germany
Jan Stallkamp: Mannheim Institute of Intelligent Systems MIISM, dpt. For Automation in Medicine and Biotechnology, Mannheim, Germany
Philipp Beckerle: FAU Erlangen, Institution for Autonomous Systems und Mechatronics, Erlangen, Germany
Markus Kühne: DB Systemtechnik GmbH, Frankfurt, Germany

1 Introduction

The use of robotic assistance systems in the OR is expected to decrease complication rates as well as increase the precision of surgical procedures [1]. Robotic assistance systems such as the novel robotic biopsy system guidoo (BEC GmbH, Germany) and the robotic angiography system Artis zeego (Siemens Healthineers AG, Germany) enable fast and precise needle placement for the diagnosis and therapy of cancer patients with less radiation exposure and injuries of tissue [2]. In robot-assisted surgeries, robotic assistance systems, medical devices and healthcare professionals collaborate in close proximity, resulting in a heightened risk of collision [3]. Research on handling such collisions is subdivided into avoiding collisions and minimizing injuries in humans caused by a collision with a robotic assistance system [4].

Current medical robotic assistance systems for instance limit their power and force or monitor their speed and distance to minimize injuries [5, 6]. To avoid collisions, a monitoring system is used for the collision-free trajectory planning [3, 7, 8]. However, these concepts need access to the robot's control unit and have so far not been successfully applied to complex and unpredictable surgical procedures like the robot-assisted needle placement.

To the best of our knowledge, augmented reality (AR) has not been previously applied to avoid collision of medical robotic assistance systems in the OR. Only one research paper demonstrated the use of AR with a medical robotic assistance system by visualizing the initial configuration of the da Vinci surgical system [9]. AR in the OR is mainly used to overlay imaging data into the surgeon's field of view [10–13].

In this work, a novel companion system is designed for collision avoidance in robot-assisted needle placement. In robot-assisted needle placement, collisions may occur during robot movements or due to an inadequate workflow. The companion system aims to prevent predictable

Open Access. © 2021 The Author(s), published by De Gruyter. This work is licensed under the Creative Commons Attribution 4.0 License.

collisions by planning the intervention preoperatively and transferring these results into the OR via augmented reality (AR). Research also encourages the integration of human anticipation of the collaboration partner's actions for a more natural human-robot collaboration [6]. Hence, the companion system visualizes future robotic trajectories and poses via AR and thus empowers healthcare professionals to anticipate unforeseen obstacles on the robot trajectory and to avoid unpredictable collisions in a complex surgical environment.

2 Material and methods

The medical devices for robot-assisted needle placement as well as the design of the companion system and the preliminary experiments with users are presented below.

2.1 Medical devices for robot-assisted needle placement

During the needle placement, a robotic angiography system such as the Artis zeego enables intraoperative imaging to visualize the position of the needle (see Figure 1). The guidoo assists the needle placement by positioning a needle sleeve next to the insertion point to mechanically guide the needle. Whereas the Magnus operating table (Maquet GmbH, Germany) facilitates the patient positioning. These three robotic assistance systems are operated by a control unit. In addition, a ceiling supply unit, several lamps and monitors are required during the surgery.

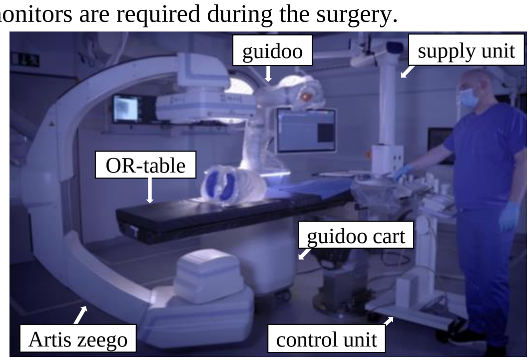

Figure 1: Medical devices for robot-assisted needle placement

2.2 Companion system

The companion system consists of two applications: the planning and the AR application. Depending on the selected needles, the planning application preoperatively calculates the collision-free positions and poses for the medical devices (OR configuration) and defines a collision-free surgical workflow on a PC. For collisions avoidance, a safety distance of 4 cm is assumed as a reasonable distance between the medical devices. This safety distance was derived from the current common distance between the mobile guidoo cart and the C-arm used in experimental practice. The planning application was developed in the game engine Unity (Unity Technologies, USA) using the 3D computer graphics software Blender (Blender Foundation, Netherlands) for modelling kinematic chains of robotic arms and the BioIK toolbox [14] for solving the inverse kinematics. The input panel shown on the upper left in Figure 2 is used to operate the planning application.

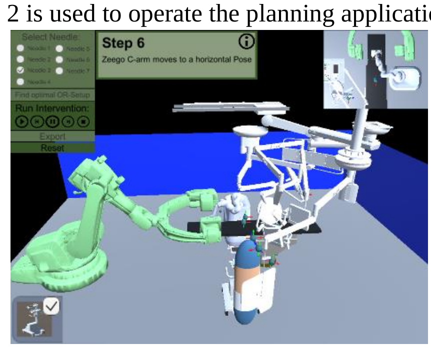

Figure 2: Planning application with an input panel and the digital twin of the hybrid OR including the medical devices for robot-assisted needle placement

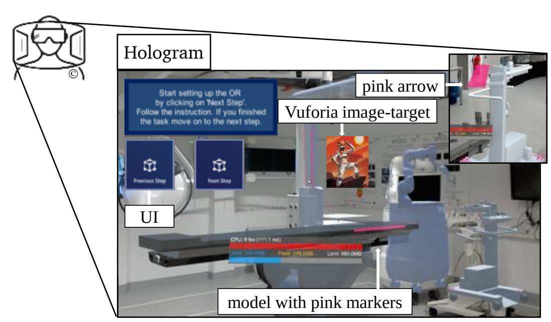

Figure 3: Hologram of the AR application including the user interface (UI) and the models of the medical devices

The calculated OR configuration is then transferred to the AR application, here we used the HoloLens (Microsoft Corporation, USA). The AR application guides surgeons intraoperatively step by step through setting up the hybrid OR and the surgery by visualizing future robotic trajectories, poses and device positions. In each step, only one device changes its position or robotic pose, a pink arrow points to the new position and the UI describes the actions to be carried out. The surgeons control the AR application through buttons that are operated by gestures.

Similar to the planning application, the AR application was developed by using Unity, Blender and the BioIK toolbox. The interactable buttons were created with the Mixed Reality Toolkit (Microsoft Corporation, USA). Registration and tracking for the correct fitting of the virtual content into reality is implemented with an image target of the Vuforia software development kit (PTC Inc., USA). Each model is enhanced with pink lines for clear positioning (see Figure 3).

2.3 Preliminary experiments design

Four questions were examined to investigate the AR application's suitability for collision avoidance:

1. Which positioning accuracy of medical devices can be achieved with the AR application?
2. Is the user able to follow the predefined workflow presented by the AR application?
3. Are collisions prevented by using the AR application?
4. What is the user experience with the AR application?

A total of six participants with no medical experience were recruited. After verbal and written instructions on the study design and purpose as well as the handling of the devices, participants were asked to set up the hybrid OR by following the workflow presented by the AR application. This included repositioning of the guidoo and the control unit as well as changing the poses of the operating table and the ceiling supply unit in four successive steps.

To measure the deviation in position and rotation between the predefined ideal location and real location, the laser measure GLM 50 Professional (Robert Bosch GmbH, Germany) was connected to the rotation mount CRM1L(/M) (Thorlabs GmbH, USA) using an adapter. Errors and questions of participants that occurred during setting up the OR were recorded and characterized by the Human-HAZOP [15]. After setting-up the hybrid OR, the participants completed the meCUE questionnaire [13] to evaluate their user experience.

3 Results

The boxplots in Figure 4 illustrate on the y-axis the distance between the ideal device position and the device position measured in the study for each device and direction. Neglecting outliers, medical devices were positioned with a deviation of 0.7 to 19.5 cm from the ideal position. The regression line in Figure 5 indicates that as the distance to the image target (x-axis) increases, the positioning accuracy of the devices decreases (y-axis). The deviation from the ideal device rotation ranges from -1.75° to 2.25°.

During the study participants asked five questions. Figure 6 depicts the frequency and classification of these questions for each step using the Human-HAZOP. Neither of them caused a deviation from the workflow nor a collision.

The evaluation of the AR application with the meCUE questionnaire indicates a usability of 6.39 and usefulness of 5.94 (1= strongly disagree to 7 = strongly agree) (see Figure 7). The overall experience was rated with +3.8 (-5 = as bad to +5 = as good).

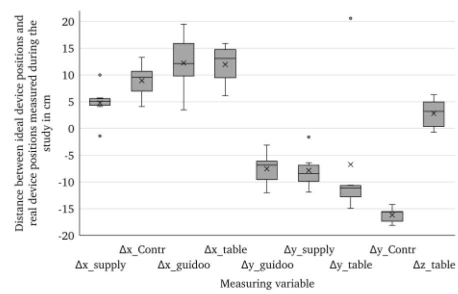

Figure 4: Boxplots for each medical device and direction

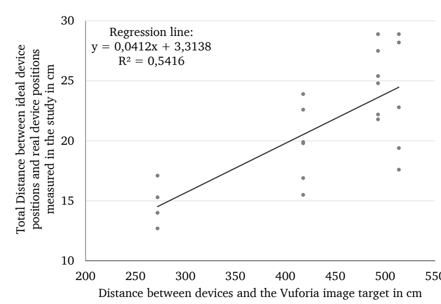

Figure 5: Scatter plot with regression line for each device

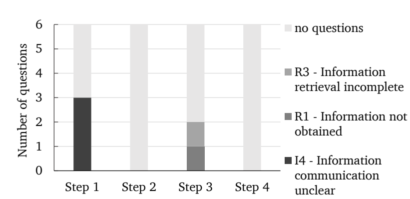

Figure 6: Frequency of questions during each step

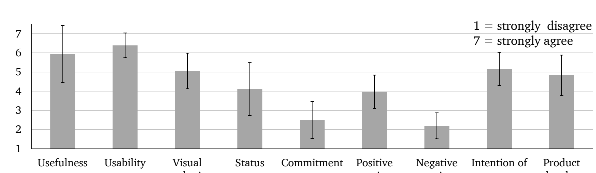

Figure 7: Results of the meCUE questionnaire regarding the user experience of the AR application

4 Discussion and conclusion

The preliminary experiments with users indicate that the AR application effectively communicates the predefined workflow. Consequently, collisions resulting from an inadequate workflow are reduced. To further avoid misunderstandings, the instructions could be specified by using additional visual aids such as a demo video. However, collisions caused by positioning inaccuracies are likely to appear, since the deviations between the ideal device position and the real device position measured in the study exceed the predefined safety distance of 4 cm (see Figure 4).

The meCUE questionnaire illustrates a positive user experience. Yet, the significance of modules such as the usability is higher than the significance of modules such as usefulness or product loyalty, which might be due to the non-medical background of the participants.

In order to improve the positioning accuracy of the AR application, further investigations are needed to detect and eliminate interfering parameters. Alternatively, a device tracking system can be used to determine the deviation between the current and desired device position. Following these optimizations, a user study with healthcare professionals in a clinical environment is suggested.

Research funding: This research paper is part of the Research Campus M^{2}OLIE and funded by the German Federal Ministry of Education and Research (BMBF) within the Framework “Forschungscampus: public-private partnership for Innovations” under the funding code 13GW0389A.

Author contributions: All authors have accepted responsibility for the entire content of this manuscript and approved its submission.

Conflict of interest: Authors state no conflict of interest.

Informed consent: Informed consent has been obtained from all individuals included in this study.

References

[1] A. Hussain, A. Malik, M. U. Halim und A. M. Ali, „The use of robotics in surgery: a review“, *International journal of clinical practice*, Jg. 68, Nr. 11, S. 1376–1382, 2014.

[2] Fraunhofer-Institut für Produktionstechnik und Automatisierung, *guidoo.* [Online]. Verfügbar unter: https://pamb.ipa.fraunhofer.de/de/unsere_projekte/guidoo.html (Zugriff am: 28. Oktober 2020).

[3] Q. C. Nguyen, Y. Kim, S. Park und H. Kwon, „End-effector path planning and collision avoidance for robot-assisted surgery“, *Int. J. Precis. Eng. Manuf.*, Jg. 17, Nr. 12, S. 1703–1709, 2016, doi: 10.1007/s12541-016-0197-3.

[4] S. Robla-Gomez, V. M. Becerra, J. R. Llata, E. Gonzalez-Sarabia, C. Torre-Ferrero und J. Perez-Oria, „Working Together: A Review on Safe Human-Robot Collaboration in Industrial Environments“, *IEEE Access*, Jg. 5, S. 26754–26773, 2017, doi: 10.1109/ACCESS.2017.2773127.

[5] O. Bendel, *Pflegeroboter*. Wiesbaden: Springer Gabler, 2018.

[6] H.-J. Buxbaum, *Mensch-Roboter-Kollaboration,* 1. Aufl. Wiesbaden: Springer Fachmedien Wiesbaden; Imprint: Springer Gabler, 2020.

[7] J. Raczkowsky, P. Nicolai, B. Hein und H. Wörn, „System Concept for Collision-Free Robot Assisted Surgery Using Real-Time Sensing“ in *Studies in computational intelligence*, Bd. 466, *Frontiers of intelligent autonomous systems*, S. Lee, K.-J. Yoon und J. Lee, Hg., Berlin: Springer, 2013, S. 391–399, doi: 10.1007/978-3-642-35485-4_34.

[8] S. Hameed und O. Hasan, „Towards autonomous collision avoidance in surgical robots using image segmentation and genetic algorithms“ in *2016 IEEE Region 10 Symposium (TENSYMP)*, 2016, S. 266–270, doi: 10.1109/TENCONSpring.2016.7519416.

[9] M. Stoljar und O. Burgert, „Präoperative Planung roboterassistierter Eingriffe mithilfe von augmentierter Realität und Robotik-Simulation“ in *CURAC*, Leipzig, 2018, S. 51–56.

[10] R. Dörner, W. Broll, P. Grimm und B. Jung, *Virtual und Augmented Reality (VR/AR)*. Wiesbaden: Springer Vieweg, 2019.

[11] C. Kunz, M. Hlavâc, M. Schneider, B. Hein, D. Puljiz, S. Peikert, „A System for Augmented Reality Guided Ventricular Puncture Using a HoloLens: Design, Implementation and Initial Evaluation“ in *CURAC*, Leipzig, 2018, S. 132–137.

[12] S. Ilango, H. Dava und T. Ortmaier, „Self-Localized Multi-Projector Systems for Surgical Interventions: A User Study“ in *CURAC*, Reutlingen, 2019, S. 223–228.

[13] A. Mewes, F. Heinrich, B. Hensen, F. Wacker, K. Lawonn und C. Hansen, „Concepts for augmented reality visualisation to support needle guidance inside the MRI“, *Healthcare technology letters*, Jg. 5, Nr. 5, S. 172–176, 2018.

[14] S. Starke, N. Hendrich und J. Zhang, „Memetic Evolution for Generic Full-Body Inverse Kinematics in Robotics and Animation“, *IEEE Transactions on Evolutionary Computation*, Jg. 23, Nr. 3, S. 406–420, 2019.

[15] humanfactors101.com, *Core topic 3: Identifying human failures.* [Online]. Verfügbar unter: https://humanfactors101.files.wordpress.com/2016/04/identifying-human-failures.pdf (Zugriff am: 8. Januar 2020).