Virtual Environments in Surgery: Synthetic SLAM Validation in Knee Arthroplasty

Arne SCHIERBAUM [1], Tobias NEISS-THEUERKAUFF [2], Thomas LUHMANN [1], Frank WALLHOFF [2], Till SIEBERTH [1]
[1] Institute for Applied Photogrammetry and Geoinformatics, Jade Hochschule, University of Applied Sciences, Oldenburg, Germany;
[2] Institute for Technical Assistive Systems, Jade Hochschule, University of Applied Sciences, Oldenburg, Germany

Keywords: 3d scanning, SLAM, Blender, simulation, surgery, knee arthroplasty

Abstract

Knee arthroplasty is a commonly performed surgical procedure in which computer-assisted and partially robot-guided systems are increasingly used to improve precision [1]. Traditionally, these systems rely on optical markers that are fixed to the femur and tibia. However, these invasive markers require drilling, which can prolong the healing process and increase the risk of infection [2]. This work aims to lay the foundation for markerless navigation, eliminating the need for such fixation.

To achieve this, the visible surface of the knee is captured using SLAM (Simultaneous Localization and Mapping) with a handheld trinocular camera system [3]. Challenges include the low-texture surface, reflections caused by wet surfaces, and the movement of the knee during surgery. Evaluating the accuracy of the SLAM-based systems is difficult, due to too few suitable test datasets and the limited availability of real 3D medical data. In addition, realistic annotated images of bones are missing, which are necessary for AI-based masking the knee during SLAM.

This paper presents a simulation environment developed using Blender [4], in which surgical scenes are created based on anatomical 3D models (Figure 1). The system simulates camera motion and generates image data for knee reconstruction, which can be evaluated against known ground truth. The simulation not only supports the geometric optimization of the camera system but also provides direct access to the image position of the bone. As a result, it eliminates the need for separate bone segmentation, which in real scenarios is typically performed using deep learning methods that remain prone to error [5]. These segmentation inaccuracies can significantly impact SLAM performance and make its evaluation more difficult. By generating precise masks alongside the synthetic images, the simulation avoids this source of uncertainty and enables a more accurate and isolated assessment of SLAM algorithms. At the same time, the simulation environment is used to automatically generate training data for segmentation and to improve masking.

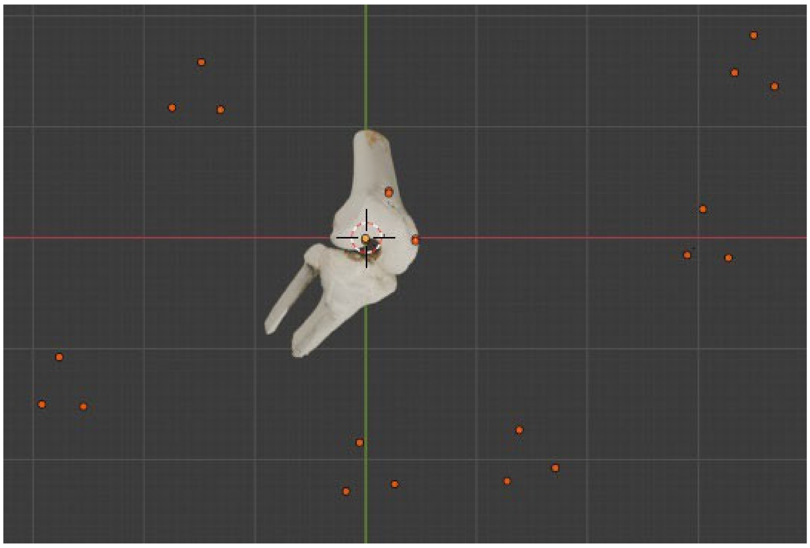

Figure 1: Viewpoints of the trinocular camera system (orange dots) on an anatomical 3D model in Blender

The framework thus provides a robust basis for future integration into clinical workflows. To further enhance validation, a physical test setup has been developed in parallel using a robotic arm equipped with the actual camera system as its end-effector. This setup enables the reproducible acquisition of image sequences from real knee models and allows direct comparison between synthetic and real data within the same evaluation pipeline. In addition, future developments of the simulation environment will incorporate dynamic motion and anatomical variability to enable more comprehensive validation of markerless navigation approaches.

References

[1] Moret, C.S. & Hirschmann, M.T., 2021: Navigation und Robotik in der Knieendoprothetik. Arthroskopie, 34 (5), 351-357.

[2] Stübig, T., Windhagen, H., Krettek, C. & Ettinger, M., 2020: Computer-Assisted Orthopedic and Trauma Surgery. Deutsches Ärzteblatt international, 117 (47), 793-800. doi.org/10.3238/arztebl.2020.0793

[3] Schierbaum, A., Neiß-Theuerkauff, T., Luhmann, T., Wallhoff, F., Sieberth, T., 2024: Investigations on 3D reconstruction of bones in surgery using a handheld trinocular camera system. Optical 3D Metrology Workshop, Brescia, https://doi.org/10.5194/isprs-archives-XLVIII-2-W7-2024-145-2024

[4] Blender Foundation, 2023: Blender (Version 4.0), https://www.blender.org/

[5] Neiß-Theuerkauff, T., Schierbaum, A., Luhmann, T., Sieberth, T., Wallhoff, F., 2024: Semantic bone structure segmentation in 2D image data: Towards total knee arthroplasty. Artificial Intelligence XLI - 44rd SGAI International Conference on Artificial Intelligence, AI 2024, Cambridge, UK, December 17-19, 2024, Proceedings. Lecture Notes in Computer Science (LNCS), Springer, https://doi.org/10.1007/978-3-031-77915-2_29