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Accuracy Evaluation of Image-Based Virtual Fixtures in Robotic Laminectomy

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Abstract

The accuracy of image-based computer assisted orthopedic surgery highly depends on the accuracy of the registration step as well as image acquisition, planning and tool calibration. In this paper the accuracy of those steps is evaluated exemplarily for a robotic laminectomy.

A high-resolution test bench was designed to compare the actual location of an object and the position to which the robotic system guides the surgical tool according to the image-based plan.

Depending on the distance between the patient reference array and the tool array, average accuracies from 0.14 mm ± 0.17 mm to 0.42 mm ± 0.15 mm with a maximum error of 0.59 mm were measured.

This very high accuracy is in the range of the thickness of the spinal dura mater.

1 Introduction

In robot-assisted surgery, virtual fixtures can be used to define the borders of a region in which the surgeon can freely move the end-effector, such as a burr handpiece (Bowyer et al., 2014). The robot limits the workspace based on a planned volume, which is either based on image-free kinematic planning, e.g., the volume of an implant, or based on CT-data, e.g., for bone removal while preserving critical structures in laminectomy in spine surgery (Sugano, 2013). This paper focuses on image-based robot assisted laminectomy.

Robot motion control can be based either on tracking the robot base and using a calibrated kinematic model (Tarwala & Dorr, 2011) or on direct tool tracking (Knappe et al., 2003). Direct tool tracking has the advantage that kinematic inaccuracies or robot elasticities can be corrected based on real time robot motion control. Apart from the accuracy of real-time motion compensation based on optical tracking

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(Vossel et al., 2021), the accuracy of the virtual fixtures highly depends on image acquisition, planning and registration as well as tool calibration.

In this paper we evaluate the maximal achievable accuracy of a CT-based planning of virtual fixture boundaries for laminectomy in a technical laboratory setup using the Surgivisio imaging system (eCential Robotics, Gière, France, 2018).

To the best of the authors' knowledge, clinical accuracy requirements for laminectomy are not yet defined in literature. To protect the sensitive structure in the spinal canal, the intact dura mater must be preserved, meaning that the high-speed milling tool motion must be limited to the ventral surface of the lamina. Even though two thirds of the lamina's internal surface are covered by the ligamentum flavum (Zarzur, 1984), the remaining third is in direct contact with the dura mater (De Andrés et al., 2009). The thickness of the dura mater, which varies between 270 to 350 µm (Reina et al., 2009), must therefore be taken as lower boundary for the required accuracy.

2 Materials and Methods

A new version of the MINARO HD system (Vossel et al., 2021) with three degrees of freedom is used for these experiments, with a standard high-speed burr (Anspach eG1 High Speed Electric System, DePuy Synthes, Raynham, MA, U.S.) attached as end effector. A passive array is mounted next to the burr adapter for optical tracking with the fusionTrack500 tracking camera (Atracsys LLC, Puidoux, Switzerland). The burr tip is calibrated in relation to the array using a specially designed calibration block with a hemispherical notch with the same diameter of 4 mm as the milling tool. The calibration block itself was calibrated beforehand by pivoting using a ball shaped pointer of same diameter.

The robotic system is controlled in a synergistic hands-on mode with an underlying admittance control (Newman, 1992). The surgeon grabs the milling tool at its handle and can guide the robot by applying forces, whereas virtual fixtures are enforced based on real-time tracking so that the milling tool is only movable within the previously planned volume.

For the accuracy evaluation a high-resolution test bench was designed, which is reconfigured thrice during the experiment. All four configurations can be seen in figure 1.

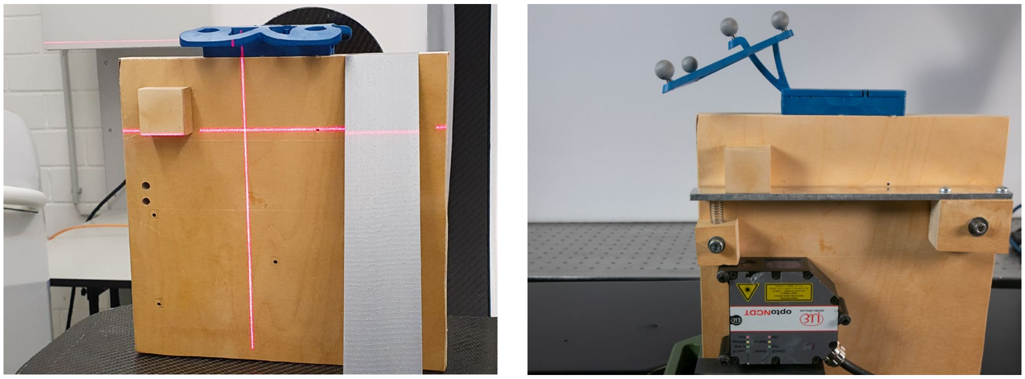
The 3D scans are acquired using the Surgivisio imaging system (eCential Robotics, Gière, France, 2018), which instantaneously performs an auto-registration based on a fixed patient reference unit with a calibration phantom attached (Boudissa et al., 2020; Lavallee et al., 2018). The framework of the test bench is a wooden panel with such a Surgivisio patient reference unit attached to it.

Before the scan, a small wooden block is glued to the panel and the Surgivisio calibration phantom is attached to the patient reference unit. In the resulting image, the lower border of the wooden block is planned as virtual limit for the milling tip position in a self-developed planning system.

In the second step, the position of the small wooden block is directly transferred to the laser sensor. For this, the laser distance sensor optoNCDT 2300-20 (Micro-Epsilon Messtechnik GmbH & Co. KG, Ortenburg, Germany) with an accuracy of 4 µm and a spring-loaded metal bar are mounted onto the panel. The Surgivisio calibration phantom is exchanged by a patient array. The position of the metal bar, which is pushed against the wooden block, is measured by the laser sensor, which is the ground truth value and to which the later readings will be compared to.

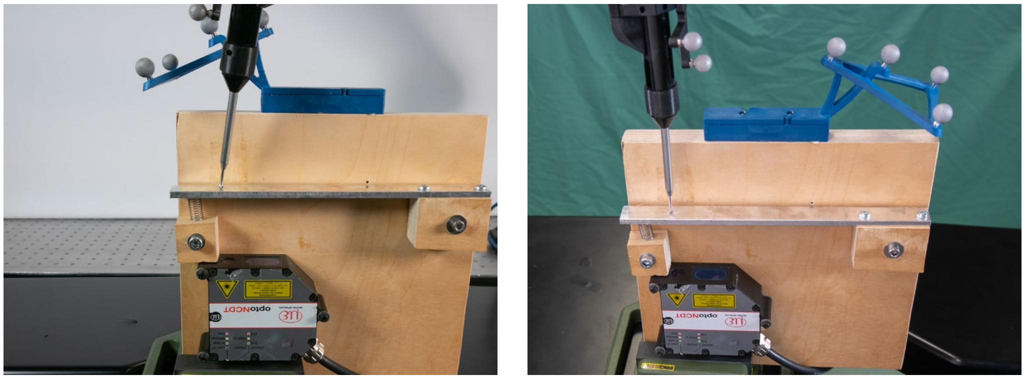
In the third step, the wooden block is removed so that the metal bar can swing upwards by the force of the spring and the surgeon does not see the planned boundary.

The patient array can be mounted in two different orientations onto the reference unit with different distances to the planned volume, which are both tested in this experiment (step three and four of figure 1). The robot end-effector is then guided downwards by the user until the movement is limited by the virtual fixture. The laser sensor reading is compared to the ground truth value.



Step 1: CT scan of the small wooden block with the Surgivisio calibration phantom.

Step 2: Acquiring the ground truth value with the laser sensor.



Step 3: Accuracy evaluation with reference array close to tool array.

Step 4: Second possible mounting orientation of reference array.

Figure 1: All four steps of the test setup.

This experiment is performed five times to gain a total of ten accuracy measurements, five for every mounting orientation of the patient array. With each of the five test runs, a new milling bit is used, and its tip position is calibrated in relation to the tool array.

3 Results

For the mounting direction of the patient array as in step three, the accuracy over the five test runs is 0.14 mm ± 0.17 mm with one outlier at 0.42 mm. For the more distant mounting direction of step four the accuracy is 0.42 mm ± 0.15 mm. The maximum accuracy error is 0.59 mm. On average, the deviation measured at the more distant mounting orientation was 0.28 mm ± 0.17 mm larger than at the mounting possibility of step 3.

4 Discussion

The evaluation of the hands-on guided virtual fixtures resulted in a maximal deviation of 0.59 mm. With bigger distance between tool array and patient array, the absolute accuracy is significantly worse. Because of this difference, it is unlikely that most of the error results from image acquisition, planning and tool calibration, since these are not affected by the distance between both arrays. Since the variance from the five measurements at proximity to the five measurements at farther distance did not increase, this is unlikely caused by measurement noise from the camera. Instead, this seems to be a slight rotational inaccuracy caused by the registration.

In general, these experiments show very good accuracy. The average measured accuracy is in the range of the thickness of the dura mater of 270 to 350 µm. Due to the low variance between the five test runs, the results might be improved though by a new calibration of the equipment used.

These accuracy results for image acquisition, planning, registration, and tool calibration with the Surgivisio system together with the fusionTrack500 camera can also be transferred to other robotic systems and other control modes like telemanipulated synergistic control or even automatic milling. For those two control modes, the breakthrough could also be measured using cutting force monitoring to further improve accuracy (Hu et al., 2014; Jiang et al., 2019). Tests have also been performed whether through acoustic monitoring of the milling process the breakthrough could be determined, which give first promising results (Ying et al., 2020). This method could be used for any interaction mode including hands-on.

With the hands-on synergistic control as evaluated in this paper, the milling result can be improved by a more conservative planning and then a visual control by the operating surgeon. At spots with left-over bone material, the initial plan could then be slightly altered to allow a perfect breakthrough over the whole length of the lamina.

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