Supporting Navigated Surgery with Pan-Tilt Controlled Laser Pointer

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Abstract:
This work introduces a laser guidance system for improving the performance of surgical navigation. It consists of a laser pointer mounted on a pan-tilt platform calibrated with the tracking system from the navigation platform. With two pan-tilt rotation axes, the laser beam of a green laser pointer can reach any location in 3D space. The calibration between the pan-tilt platform and the tracking system is done by using Levenberg-Marquardt and Least-Squares Estimation of Transformation algorithms. The registration between organ and 3D virtual model is obtained by the tracking system and therefore, the laser is also implicitly registered. Therefore, important points or the resection path of the 3D model can be projected precisely on the surface of the organ with the laser pointer.
Keywords: Pan-Tilt Platform, 3D Tracking, Least-Squares Estimation of Transformation algorithm, Levenberg-Marquardt algorithm

1 Problem

In a navigated surgery, the planning model is presented on a screen in front of the surgeon. Without the visual augmentation, it is error-prone for the surgeon to fuse the planning models with the organ mentally. One of the most common methods of augmenting reality with 3D models is the use of projectors [1]. After registering the 3D planning model to the liver, the projector can display vessels or tumours onto the liver in detail, but the brightness of the projector is a significant disadvantage in an operating room. The brightness of a normal projector is only 2×10^3 LUX, low compared to the brightness of a surgical light, which is approximately 4×10^4 LUX. The surgeon has to turn the light off and on during the operation in order to see the images projected on the liver. However, a laser pointer can easily achieve 2×10^5 LUX with only 1 mW output power, suitable for a complementary device for surgery navigation. Moreover, a pan-tilt platform is cost effective, light, and easy to transport and attach to the navigation system. Furthermore, being able to display a point on an organ quickly and precisely offers a good solution for many tasks in navigated surgery, e.g., marking critical points, entry points, resection lines (in combination with drive motion), and assessing registration precision.

2 Methods

Laser guidance systems are often proposed in medical contexts, although only few have been used in combination with a tracking system. The setup proposed in [2] uses two laser beam shooters to project two parallel lines onto the cylindrical surface of the surgical tools, and in [3] a six axes robot is used to manipulate the laser pointer. While these systems aim to target the position and orientation of the surgical tool with a rather complex setup, the goal of this work is to provide a precise positioning tool by using only two rotation axes and one laser pointer, in combination with appropriate modeling and calibration methods.
Figure 1 shows the system setup. The pan-tilt platform with the laser pointer hangs on the navigation system from CAScination [7]. Nevertheless, for the purpose of this work, the navigation software developed at Fraunhofer MEVIS was used. The navigation system consists of two parts – a display with the 3D planning model and an NDI Polaris tracking system. After landmark registration procedure, the tracking camera tracks the surgical instrument. The positions of the instrument and the planned data are displayed in real-time on the interactive screen. To augment liver surface with some important points from 3D model, two steps are necessary – modeling and calibration.
After the above two steps, the coordinates of points in the 3D planning model are converted first to the tracking system and then to the pan-tilt platform. The pan-tilt platform calculates the required rotation angles so that the laser beam points at the corresponding points on the liver.

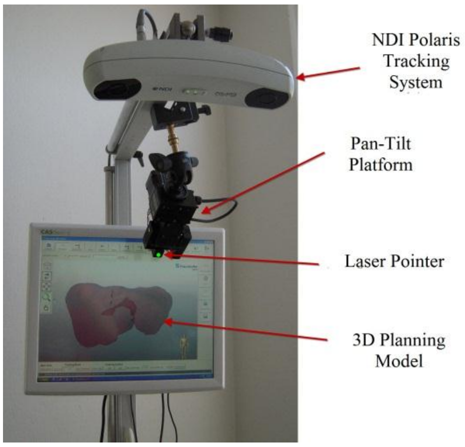

Figure 1: Pan-tilt platform fixed on the navigation system.

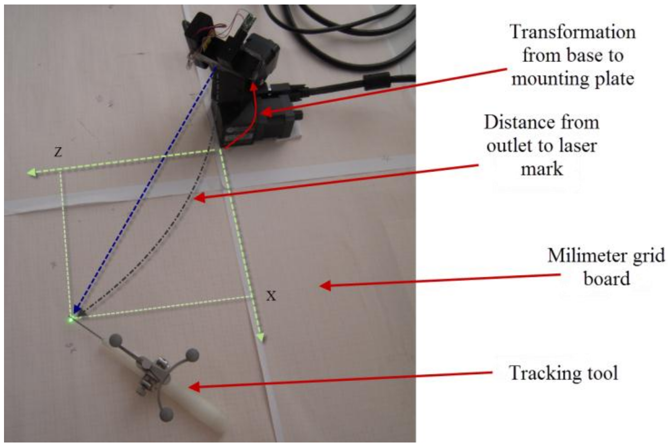

Figure 2: Kinematic modeling of pan-tilt platform with laser pointer.

Modeling

The transformation matrix between the laser pointer and the mounting plate is calculated using the following method (explained in figure2): Rotate the pan-tilt axes so that the laser beam points at the grid board and record the coordinates of this point with respect to the base of the pan-tilt platform, after which the coordinates of this point with respect to the mounting plate can be calculated using the rotation angles. The tracking system is used to measure the distance between the pointer outlet and the point on the board, and the distance can represent the coordinates of this point in the laser coordinate system. In the same way, acquire coordinates of four points in both coordinate systems. Thereafter, using the least-squares estimation of transformation algorithm [4], the transformation matrix between the laser pointer and the mounting plate on the pan-tilt platform can be calculated. After modeling, the whole pan-tilt platform will be mounted on the navigation system.

Calibration

At the beginning of the process, the registration between the tracking system and the 3D model is achieved by matching two point patterns acquired in both coordinate systems.
To acquire the transformation matrix between the tracking system and the pan-tilt platform, the coordinates of four points in both coordinate systems should be obtained. The key problem of this project is to calculate the coordinates of four points in the pan-tilt coordinate system.
The solution is this: The laser pointer points at four arbitrary points one by one (showed in figure 4); the angles of two rotation axes with respect to each point are received from the pan-tilt platform. Simultaneously, use the tracking instrument to acquire the coordinates of each point with respect to the tracking coordinate system. Then the distances of any two points can be calculated using the acquired coordinates.
Knowing the distances and angles, six equations with four variables $\{K_A, K_B, K_C, K_D\}$ can be formulated. To solve this nonlinear over-determined equation set, the Levenberg-Marquardt algorithm is used [5]. After calculating $\{K_A, K_B, K_C, K_D\}$, the coordinates of these four points with respect to the pan-tilt base can be calculated using angle information again.
Finally, as the coordinates of these four points in both coordinate systems are available, the calibration of pan-tilt platform and tracking system is achieved by using the least-squares estimation of transformation algorithm.

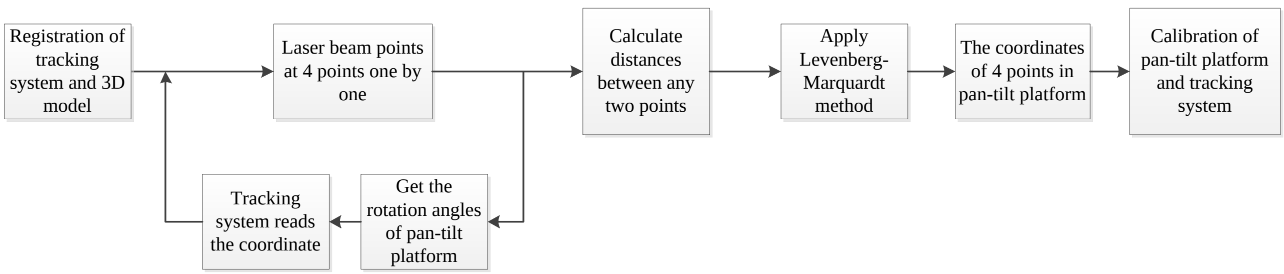

Figure 3: Calibration procedure between laser system and tracking system.

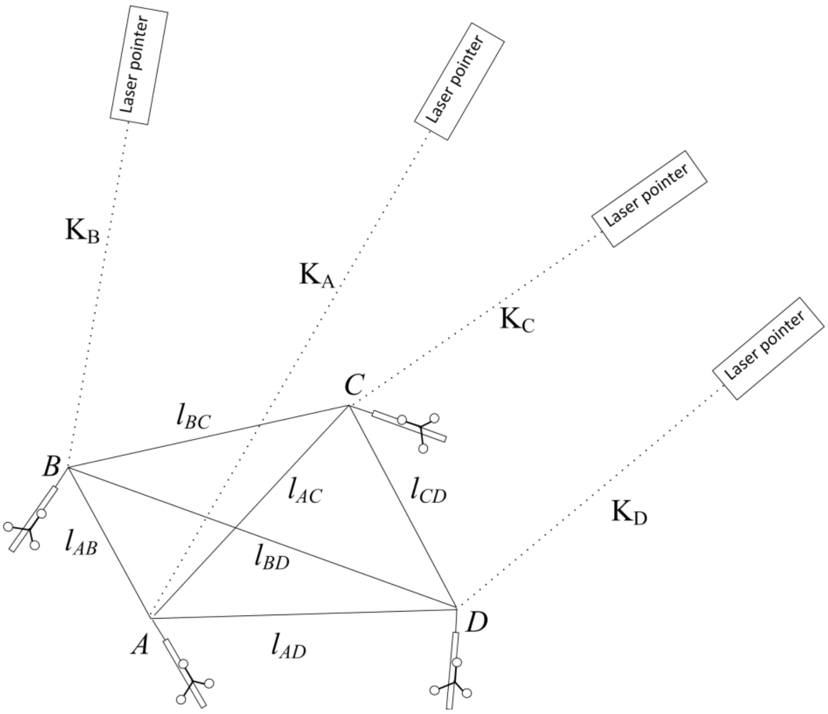

Figure 4: Calibration between the laser system and the tracking system.

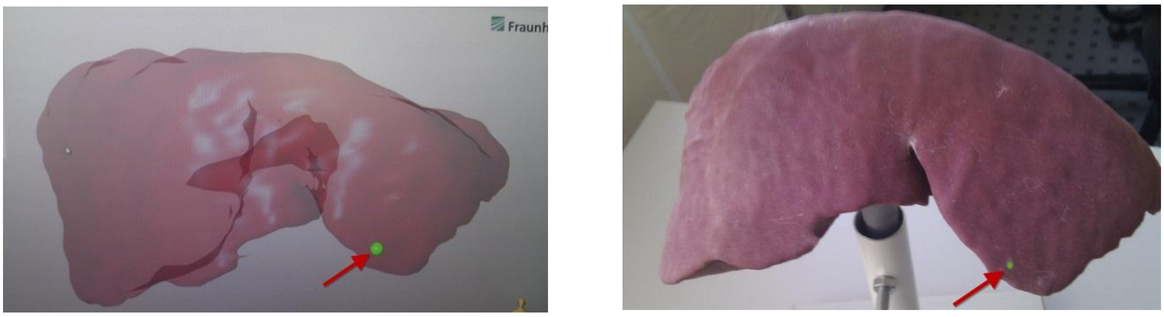

Figure 5: Augmenting one point defined in 3D planning model onto the liver.

The pan-tilt platform is now implicitly registered with 3D model; the predefined points in the model can be augmented onto the liver (shown in figure 5).

3 Results

To evaluate the calibration, a millimetre grid board and a tracking instrument are used.

The evaluation method is explained in figure 5: Put the tracking instrument on the cross of a millimetre board and make the laser beam follow the instrument tip. Due to inaccuracy in modeling, calibration error, and resolution limits of the pan-tilt platform, the laser beam will be shifted a slight amount from the instrument tip. The distance between the instrument tip and the laser beam is defined as the error. Altogether, 144 measurements were recorded, for which six calibrations were done. In each of the four predefined regions on the millimetre board, six errors were measured.

Table 1 Mean - variance (mm-mm^2) of error in testing.

	Region 1	Region 2	Region 3	Region 4	Average
Calibration 1	2.2-0.47	1.6-0.09	1.3-0.01	1.9-0.06	1.75-0.16
Calibration 2	0.8-0.03	0.7-0.02	0.8-0.02	0.9-0.01	0.8-0.02
Calibration 3	1.3-0.02	0.7-0.01	0.7-0.01	1.4-0.04	1.03-0.02
Calibration 4	1.3-0.04	0.8-0.01	0.9-0.02	1.4-0.04	1.1-0.03
Calibration 5	1.5-0.01	0.5-0.01	0.6-0.01	2.1-0.02	1.18-0.01
Calibration 6	1.6-0.1	1.1-0.01	0.9-0.02	2.1-0.03	1.43-0.04
Average	1.45-0.11	0.9-0.025	0.87-0.015	1.63-0.03	1.21-0.045

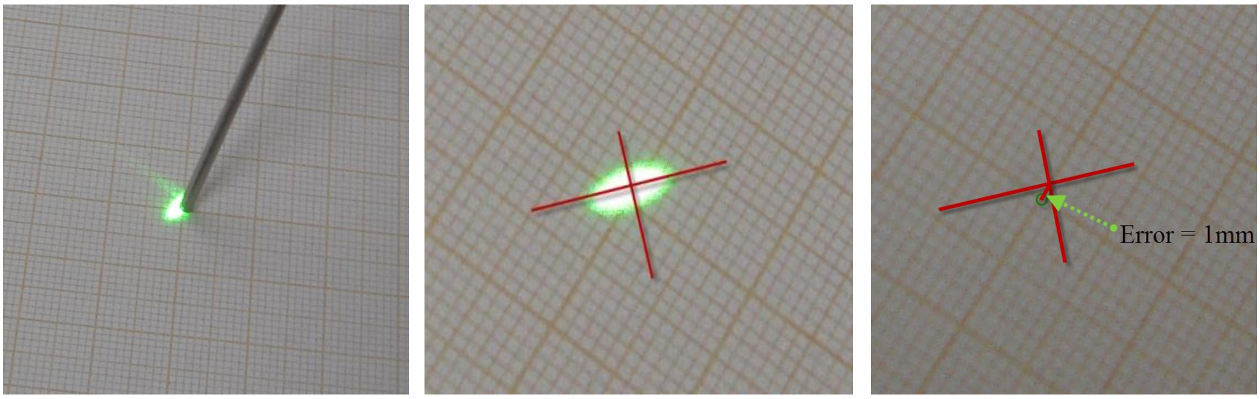

Figure 6: Evaluation method – Left: Instrument tip with laser mark; Middle: The laser mark with cross at the centre; Right: Error between two crosses.

The total average mean and variance of the 144 measurements are 1.21 mm and 0.045 mm^2; however, the laser mark has an elliptic size of 5 x 3 mm, which is much larger than the error. So, a better laser pointer will be used in the future development to match the accuracy of the calibration.

4 Discussion

The proposed laser guidance system offers a meaningful improvement of navigation systems, in that the user can easily see the critical points on the organ. The surgeon can choose a point on the 3D virtual model, for which the laser pointer will efficiently display that point. Furthermore, the pointer can slowly follow a line marked on the virtual model, e.g., resection line, which gives seamless guidance for the surgeon. Also, visually assessing the registration error could fit well in overall workflow: A visible organ landmark can be targeted with the laser pointer.

Compared to a projector, the laser guidance system is not capable of showing the anatomy of the organ in detail. However, it can compete with the brightness of the light in the operating room. From another point of view, the laser system can complement a projector.

Another open issue is the organ motion, which is often present in navigated surgery. Until now, only static models were used in the lab environment. Further development of this system would take organ motion into account. If the motion is known or measurable, registration could be updated in real time. In this way, the laser beam will synchronise with the organ's motion and continuously point at the defined target.

5 Reference

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