Augmented Reality and Robotic Navigation System for Spinal Surgery

Matteo Boles[1], Junling Fu[1], Elisa Iovene[1], Francesco Costa[2], Giancarlo Ferrigno[1], Elena De Momi[1]

[1]*Department of Electronics, Information and Bioengineering, Politecnico di Milano, Milan, Italy*

[2]*Department of Neurosurgery, Fondazione Istituto Nazionale Neurologico, "C. Besta", Milan, Italy*

INTRODUCTION

Robotic spinal surgery requires the surgeon to drill a hole inside the vertebral body of the patient at the level of the pedicle and insert a screw afterward while ensuring to avoid causing damage to surrounding vulnerable structures, such as nerve roots, spinal cord, and blood vessels. To achieve this, computer-assisted navigation (CAN) and robotic guided techniques are frequently adopted to assist surgeons. The CAN-based method allows surgeons to see the driller's position on a screen in real-time, however, requires great hand-eye coordination. In the latter one, robots are usually adopted as tool guidance systems. Operations such as the drilling, are still manually performed by surgeons to control the driller position accurately and stop timely, which may introduce lesions into sensitive tissues.

To tackle the above-mentioned problems, augmented reality (AR) can cooperate with the robotics prototype to achieve real-time navigation and control of the path and depth during surgical operations. Besides,different techniques have been investigated in AR applications to align the virtual model with the real one [1]. Manual-based approaches showed the difficulty in assessing relative depths of physical and virtual models while external tracking system-based method could inevitably introduce errors when computing the transform matrix from the markers to its view origin.

Besides, automatic drilling also has been explored and various kinds of sensors utilized to acquire signals such as force [2], sound [3] and vibration [4]. However,these signals can be easily affected by external noise. Also, the sensor-based technique utilizes the threshold algorithms, which may result in erroneous transition detection with inappropriate threshold values.

MATERIALS AND METHODS

In this paper, an AR-based robotic navigation system for spinal surgery was developed. CT dataset of a vertebral column (UWSpineCT dataset, Imperial College of London) was segmented and processed using 3D Slicer. The real vertebral model is made of Polylactic Acid (PLA) material using a 3D printer, with 20-micron layer resolution ultra-smooth surfaces.

As shown in Fig.1, the real model is positioned inside a sponge and covered with another one to resemble skin, fat and muscle of human body. Fiducial-based registration approach was adopted to match the virtual model with the real one using four 3D printed fiducial markers which are glued on the sponge. As shown in Fig.2, fiducials were located in the real world using a 3D printed pen equipped with a QR code to track the position of its tip and automatically matched with their virtual counterparts by computing the translation and rotation matrix through the Singular Value Decomposition (SVD) algorithm.

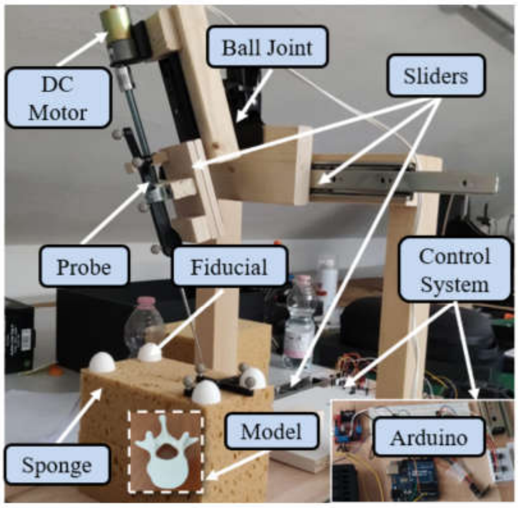

Fig. 1: Prototype of the developed robotic system.

The robotic prototype shown in Fig. 1 is composed of three parts, namely the mechanical structure, the motor drilling system, and the control system. The mechanical structure has 6 Degree-of-Freedom and is composed of three sliders and a ball joint. The motor drilling system is driven by a DC motor with the probe mounted to represent the automatic drilling process. Besides, an Arduino board is adopted as the control system and connected to the wireless network using an ESP-8266 Wi-Fi module. The NDI Polaris Vicra (Northern Digital, Inc, Ontario, Canada) is used to track the position of the mounted probe.

In Fig. 2, the pre-planned path of drilling the obtained vertebra model was manually defined in 3D Slicer and then it is integrated into the hologram of the vertebra for visualization. Fig. 3 illustrates the communication diagram of the whole system. The position of the probewas integrated on the CT scans using the Plus server in real-time and displayed on a virtual screen in Fig. 2. Command will be sent from MATLAB to ROS (Robot Operating System) to stop the movement of the probe when it reaches

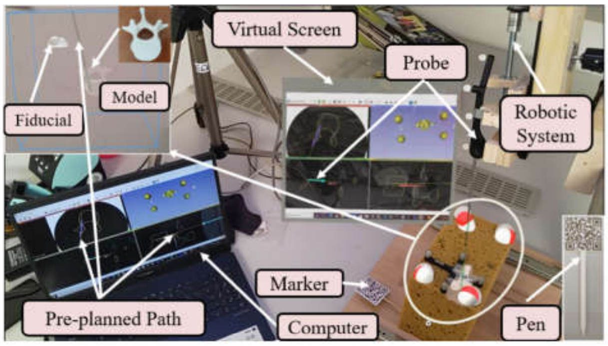

Fig. 2: Experimental setup of the proposed AR-based robotic spinal surgery navigation system.

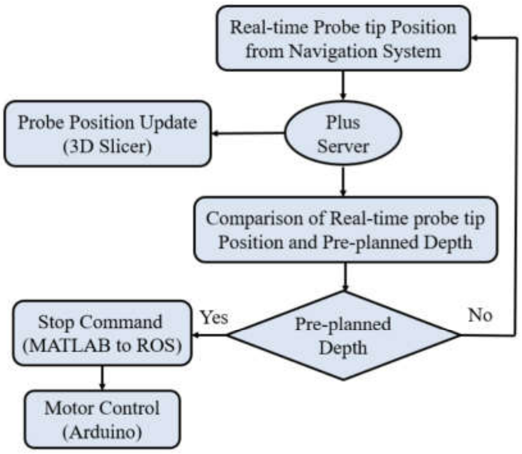

Fig. 3: Diagram of the communication of the proposed navigation system.

TABLE I: Experimental results of the target deviation and angular deviation errors.

	Frontal	Transversal	Sagittal
Target deviation (mm)	1.34 (±0.59)	0.91 (±0.40)	0.88 (±0.65)
Angular deviation (◦)	1.31 (±0.87)	0.93 (±1.55)	6.38 (±6.10)

the pre-planned position.

To verify the feasibility of the proposed navigation system, nine subjects were invited to perform the real and virtual model alignment task and position the robotic prototype in line with the entry point of the 3D printed vertebra inside the sponge looking to the virtual path displayed on the hologram and to the virtual screen in the AR application.

In this paper, performance metrics are chosen to quantitatively and qualitatively evaluate the experimental results, including both the objective and subjective metrics:

- The Fiducial Registration Error (FRE), used to define the distance between the hologram and the real model, which calculates the Root-Mean-Square distance between two fiducials point clouds.
- The target and angular deviation, between the desired path and the actual path, computed in the frontal, sagittal, and transversal planes.
- Questionnaire-based subjective method to evaluate the usability of the designed system.

RESULTS AND DISCUSSION

The experiment of aligning the real model and the virtual one is first implemented. Experimental results showed an alignment error between the real and virtual model of 4.07 ± 0.48 mm reaching a maximum of 4.85 mm and starting from a minimum of 3.37 mm.

The system positioning accuracy was then evaluated through the angular and target deviation defined in the three planes. As shown in TABLE.I, experimental results showed the target deviation errors of 1.34 ± 0.59 mm in the frontal plane while 0.91 ± 0.40 mm and 0.88 ± 0.65 mm in the transversal and sagittal plane, respectively. Considering the thickness of the cortical bone at which the driller during spinal surgery should stop has a 2 mm thickness, the error results were acceptable. In terms of angular deviation we got instead in the frontal, transversal and sagittal plane, errors $1.31° \pm 0.87°$, $0.93° \pm 1.55°$, $6.38° \pm 6.10°$ respectively.

Furthermore, subjective experimental results demonstrated that all the subjects involved in the experiment found the system easy to use without too much information to be known. Also, the questionnaire results illustrate that most of the participants preferred to rely on the virtual display to position the probe and not on the path displayed on the hologram of the vertebra probably considering the difficulty in assessing the depth of the virtual model.

CONCLUSIONS

In this paper, an AR-based robotic navigation system is developed for spinal surgery. Experimental results demonstrated the possibility of integrating the AR-based instrumentation into operating rooms for spinal surgery navigation. Participants can position correctly the robotic prototype by looking at the virtual display shown in the AR application and at the path seen on the hologram. Also, in all the trials the automatic drilling can activate and stop successfully which suggests a possible solution that could be used to automatize processes such as the drilling one in spine surgery.

REFERENCES

[1] C. M. Andrews, A. B. Henry, I. M. Soriano, M. K. Southworth, and J. R. Silva, "Registration techniques for clinical applications of three-dimensional augmented reality devices," *IEEE journal of translational engineering in health and medicine*, vol. 9, pp. 1–14, 2020.

[2] Y. Hu, H. Jin, L. Zhang, P. Zhang, and J. Zhang, "State recognition of pedicle drilling with force sensing in a robotic spinal surgical system," *IEEE/ASME Transactions On Mechatronics*, vol. 19, no. 1, pp. 357–365, 2013.

[3] Y. Torun and Ö. Pazarci, "Parametric power spectral density estimation-based breakthrough detection for orthopedic bone drilling with acoustic emission signal analysis." *Acoustics Australia*, vol. 48, no. 2, 2020.

[4] Y. Dai, Y. Xue, and J. Zhang, "Noncontact vibration measurement based thoracic spine condition monitoring during pedicle drilling," *IEEE/ASME Transactions on Mechatronics*, vol. 19, no. 5, pp. 1532–1540, 2013.