

Robot-assisted image-guided targeting for minimally invasive neurosurgery: intraoperative robot positioning and targeting experiment

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Abstract. This paper is part of an ongoing effort to develop a novel image-guided system for precise automatic targeting in keyhole minimally invasive neurosurgery. The system consists of a miniature robot fitted with a mechanical guide for needle/probe insertion. Intraoperatively, the robot is directly affixed to a head clamp or to the patient skull. It automatically positions itself with respect to predefined targets in a preoperative CT/MRI image following an anatomical registration with an intraoperative 3D surface scan of the patient facial features. In this paper, we describe the intraoperative robot positioning module and a targeting in-vitro experiment which yields an error of 1.6mm (std=1.7mm).

1 Introduction

Precise targeting of tumors, lesions, and anatomical structures with a probe or a needle inside the brain based on preoperative CT/MRI images is the standard of care in many keyhole neurosurgical procedures. The procedures include tumor biopsies, catheter insertion, deep brain stimulation, aspiration and evacuation of deep brain hematomas, and minimal access craniotomies. Additional procedures, such as tissue and tumor DNA analysis, and functional data acquisition, are rapidly gaining acceptance and also require precise targeting. These minimally invasive procedures are difficult to perform without the help of support systems that enhance the accuracy and steadiness of the surgical gestures.

Four types of support systems for keyhole neurosurgery are currently in use: 1. stereotactic frames; 2. interventional imaging systems; 3. navigation systems, and; 4. robotic systems. Stereotactic frames provide precise positioning with a manually adjustable frame rigidly attached to the patient skull. These extensively used frames provide rigid support for needle insertion, and are relatively accurate and inexpensive ($< 1mm$, USD 50K). However, they require preoperative implantation of frame screws, head immobilization, and manual adjustment

during surgery. They cause patient discomfort and do not provide real-time validation.

Interventional imaging systems produce images showing the actual needle position with respect to the predefined target [1–3]. Their key advantage is that they account for brain shift. A few experimental systems incorporate optical real-time tracking or robotic positioning devices, or augment the reality view with the imaging device output [15–17]. However, their nominal and operational costs are high and their availability is very limited. Furthermore, brain shift is a secondary issue in keyhole neurosurgeries.

Navigation systems (e.g., Medtronic, USA and BrainLab, Germany) show in real time the location of hand-held tools on the preoperative image onto which targets have been defined [4–6]. Augmented with a manually positioned tracked passive arm (e.g., Phillips EasyTaxisTM), they also provide mechanical guidance for targeting. While these systems are now in routine clinical use, they are costly (USD 250K), require head immobilization and maintenance of line-of-sight for tracking, and additional time for registration and manual arm positioning.

Robotic systems provide frameless stereotaxy with a robotic arm that automatically positions itself with respect to a target defined in the preoperative image [7–10]. Registration between the image and the intraoperative situation is done by direct contact or with video images. Two floor-standing commercial robots include NeuroMateTM (Integrated Surgical Systems, USA) and PathFinderTM (Armstrong HealthCare, UK). Their advantages are that they are rigid, accurate, and provide a frameless integrated solution. However, since they are bulky, cumbersome, and costly (US 300K), they are not commonly used.

2 System overview and protocol

We are developing a novel image-guided system for precise automatic targeting of structures inside the brain that aims at overcoming the limitations of existing solutions [11]. The system automatically positions a mechanical guide to support keyhole drilling and insertion of a needle or probe based on predefined entry point and target locations in a preoperative CT/MRI image. It incorporates the miniature MARS robot (Mazor Surgical Technologies) [12–14], originally developed for orthopaedics, mounted on the head immobilization clamp or directly on the patient skull via pins. Our goal is a robust system for keyhole neurosurgical procedures which require clinical accuracy of 1–1.5mm.

The key idea is to establish a common reference frame between the preoperative CT/MRI image and the intraoperative patient head and robot locations with an intraoperative 3D surface scan of the patient’s facial features. Once this registration has been performed, the transformation that aligns the planned and actual robot targeting guide location is computed. The robot is then automatically positioned and locked in place so that its targeting guide axis coincides with the entry point/target axis.

The system hardware consists of: 1) the MARS robot and its controller; 2) a custom robot mounting base, targeting guide, and registration jig; 3) an off-the-

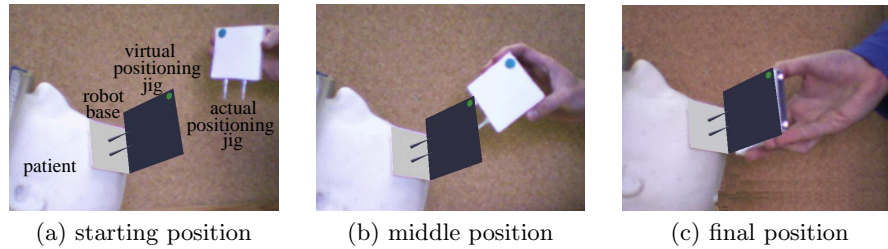


Fig. 1. Intraoperative robot positioning augmented reality images.

shelf 3D surface scanner, and; 4) a standard PC. MARS is a $5 \times 8\text{cm}^2$ cylinder, 250-gram six-degree-of-freedom parallel manipulator with work volume of about 10cm^3 and accuracy of 0.1mm. It operates in semi-active mode; when locked, it is rigid and can withstand lateral forces of up to 10N [13]. The adjustable robot mounting jig attaches the robot base to either the head immobilization frame or to skull-implanted pins. The system software modules are: 1) preoperative planning; 2) intraoperative execution; 3) surface scan processing; and 4) three-way registration. The first and last modules are described and evaluated in [19]. In this paper we describe the intraoperative robot positioning module, which is a major component of the second module and an in-vitro targeting experiment.

3 Intraoperative robot positioning

The intraoperative robot positioning module helps the surgeon place the robot base close (within 5mm) of its planned position both for skull and frame-mounted cases. Given the small robot work volume and the lack of anatomical landmarks on the skull, this coarse positioning is necessary to avoid deviations of 10mm or more from the planned position. The preoperative module is indicating that these deviations can severely restrict or invalidate altogether the preoperative plan.

The module shows the surgeon a real-time, augmented reality image consisting of a video image of the actual patient skull and a positioning jig, and, superimposed on it, a virtual image of the same jig indicating the robot base in its desired location (Figure 1). The surgeon can then adjust the position and orientation of the positioning jig until it matches the planned location. The inputs are the preoperative plan, the geometric models of the robot base and the patient face, the real-time video images, and a face/ear scan.

The goal is to compute the planned robot base position with respect to the video camera image so that robot base model can be projected on the video image at its desired planned position (Figure 2). The video camera is directly mounted on the 3D surface scanner and is pre-calibrated, so that the transformation between the two coordinate systems, $T_{scanner}^{video}$ is known in advance. A 3D surface scan of the face is acquired and matched to the geometric face model with the same method used for three-way registration as described in [19]. This

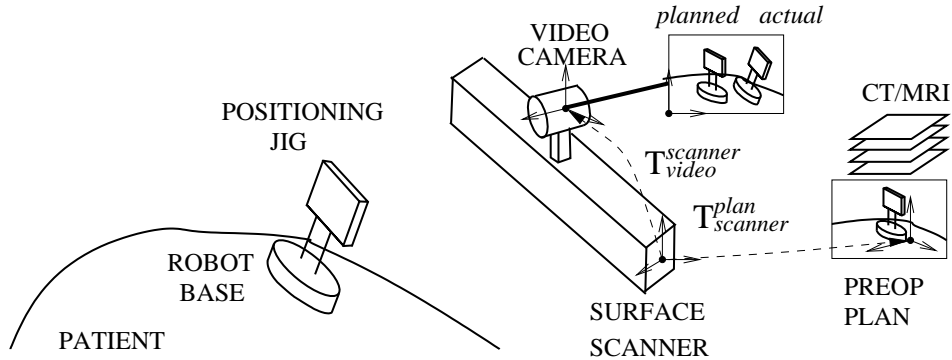


Fig. 2. Intraoperative robot positioning computation.

establishes the transformation between the preoperative plan and the scanner, $T_{plan}^{scanner}$. By composing the two transformations, we obtain the transformation between the preoperative plan and the video, T_{plan}^{video} .

4 In-vitro experiments of the entire system

This experiment aims at testing the in-vitro registration accuracy of the entire system. For this purpose, we manufactured the registration jig, a precise stereolithographic phantom replica of the outer head surface of the second student author (M. Freiman) from an MRI dataset, and a positionable robot mounting base [19]. Both the phantom and the registration jigs include fiducials at known locations for contact-based registration. In addition, the phantom includes fiducials inside the skull that simulate targets inside the brain. The phantom is attached to a base with a rail onto which slides a manually adjustable robot mounting base. The goal is to measure the Fiducial and Target Registration Errors (TRE and FRE, respectively) [18].

We used an optical tracking system (Polaris, Northern Digital, Canada – 0.3mm accuracy) as a precise coordinate measuring machine to obtain the ground truth relative locations of the phantom and the registration jig. Their spatial location is determined by touching with a calibrated tracked pointer the phantom and registration jig fiducials. The positional error of the tracked pointer at the tip is estimated at 0.5mm. The phantom and the registration jig were scanned with a video scanning system (Optigo200, CogniTens – 0.03mm accuracy). The phantom manufacturing error with respect to the MRI model is 0.15mm, as measured with the Optigo200 and our surface registration method [19].

The experiment quantifies the accuracy of the three-way registration algorithm for several targets inside the skull. In each trial, we performed three-way registration with the registration jig and for each of the targets moved the robot so that the needle guide axis coincides with the planned target axis. We inserted the optically tracked needle into the needle guide and recorded the points on its

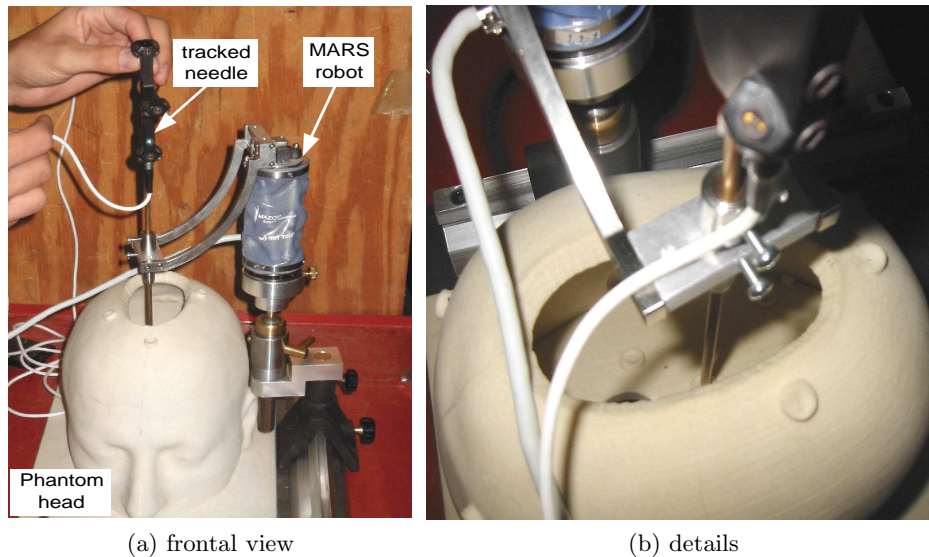


Fig. 3. In-vitro experimental setup.

trajectory to the target (Figure 3). We then computed the best-fit, least-squares line equation of these points and computed the shortest Euclidean distance between the planned and actual entry and target points, and the relative angle between the axes. Table 1 shows the results for four runs. The TRE is 1.74mm (std=0.97mm) at the entry point, 1.57mm (std=1.68mm) at the target point, and 1.60° (0.58°) for the axis orientation.

5 Conclusion

We have described a system for automatic precise targeting in minimally invasive keyhole neurosurgery that aims at overcoming the limitations of the existing solutions. The system, which incorporates the miniature parallel robot MARS, will eliminate the morbidity and head immobilization requirements associated with stereotactic frames, eliminate the line-of-sight and tracking requirements of navigation systems, and provide steady and rigid mechanical guidance without the bulk and cost of large robots. This paper presents the intraoperative robot positioning module and a targeting in-vitro experiment. It establishes viability of the surface scan concept and the accuracy of the location error of phantom targets with respect to the robot base to 1.6mm, which is close to the required 1–1.5mm clinical accuracy in many keyhole neurosurgical procedures.

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Run	phantom/scan RMS (std)	Target name	Entry error	Target error	Trajectory angular error
1	0.40 (0.13)	A	1.10	1.45	0.89
		B	1.59	0.99	0.88
		C	2.43	0.07	2.07
		D	1.41	1.97	1.48
		E	1.65	2.92	0.96
		F	2.38	2.83	0.8
2	0.39 (0.12)	A	2.10	1.61	1.10
		B	0.55	1.19	1.65
		C	1.42	0.11	1.96
		D	4.53	7.87	2.65
		E	2.78	3.17	1.34
		F	2.57	2.63	2.27
3	0.42 (0.13)	A	3.18	0.45	1.98
		B	0.99	0.38	2.42
		C	1.13	0.99	2.13
		D	0.65	1.25	2.37
		E	1.30	0.99	1.53
4	0.40 (0.12)	A	1.64	0.96	1.98
		B	1.36	0.37	1.82
		C	0.78	0.22	1.11
		D	2.37	1.45	0.80
		E	0.55	0.81	1.20
Avg(std)	0.40 (0.12)		1.74 (0.97)	1.57 (1.68)	1.60 (0.58)

Table 1. In-vitro registration results (in mm) of four trial experiments. The first column is the run number. The second column is the surface scanner registration error with respect to the phantom. The third column is the target name inside the brain. The fourth, fifth, and sixth columns are needle errors at the entry point, target, and the trajectory angular error. The last row is the average and standard deviation over all 22 trials and targets.

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