

## Miniature robot-based precise targeting system for keyhole neurosurgery: concept and preliminary results

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**Abstract.** This paper describes a novel system for precise automatic targeting in minimally invasive neurosurgery. The system consists of a miniature robot fitted with a rigid mechanical guide for needle, catheter, or probe insertion. Intraoperatively, the robot is directly affixed to the patient skull or to the head clamp. It automatically positions itself with respect to predefined targets in a preoperative CT/MRI image following a three-way anatomical registration with an intraoperative 3D laser scan of the patient anatomical features. We describe the system architecture, surgical protocol, software modules, and implementation. Registration results on 19 pairs of real MRI and 3D laser scan data show an RMS error of 1.0mm (std=0.95mm) in 2secs.

*Keywords:* computer-aided neurosurgery, medical robotics, multimodal registration.

### 1. INTRODUCTION

Precise targeting of tumors, lesions, and anatomical structures with a probe or 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, hydrocephalia treatment, deep brain stimulation (DBS), aspiration of deep brain hematomas, and minimal access craniotomies, among others. Additional procedures, such as tissue and tumor DNA analysis, and direct acquisition of functional data are rapidly gaining acceptance. These minimally invasive procedures are difficult to perform without the help of support systems that enhance the accuracy and steadiness of the surgical gestures.

There are four types of support systems for keyhole neurosurgery: 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. They have been extensively used, provide rigid support for needle insertion, and are comparatively accurate and inexpensive. However, stereotactic frames 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 acquire intraoperative im-

ages showing the actual needle position with respect to the predefined target [1–3]. A few experimental systems include optical tracking and robotic positioning devices. Their advantage is that they show the most up-to-date image, which accounts for brain shift. However, their availability is very limited and they incur in high operational costs.

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 EasyTaxis<sup>TM</sup>), they provide mechanical guidance for targeting. While they are now in routine clinical use, they are costly and require maintenance of line-of-sight for tracking, an additional registration procedure, head immobilization, and manual arm positioning.

Robotic systems provide frameless stereotaxy with an active robotic arm that automatically positions itself with respect to the target defined in the preoperative image [7–10]. The registration between the preoperative image and the intraoperative situation is done by direct contact or with video images. Two floor-standing commercial robots include NeuroMate<sup>TM</sup> (Integrated Surgical Systems, USA) and PathFinder<sup>TM</sup> (Armstrong HealthCare Ltd, UK). Their advantages are that they are frameless, that they are rigid and accurate, and that they provide an integrated solution. However, since they are bulky, cumbersome, and costly, they are not commonly used.

## 2. MATERIALS AND METHODS

We are developing a novel system for precise automatic targeting of small structures inside the brain that aims at overcoming the limitations of existing solutions. The system automatically positions a mechanical guide to support keyhole drilling and insertion of a needle or a probe based on a predefined entry point and target location in a preoperative CT/MRI image. It incorporates the versatile miniature MARS robot (Mazor Surgical Technologies, SmartAssist robot series) [11,12], originally developed for orthopaedics, directly mounted on the patient skull via pins or on the head immobilization clamp (Fig. 1a). Our goal is to develop a robust, easy-to-use system for a wide variety of neurosurgical procedures with an overall clinical accuracy of 1mm and 1° for under USD 100,000.

The key idea is to register with a 3D laser scan the unmarked preoperative CT/MRI data set with the intraoperative patient head and robot locations. The 3D laser scan of the patient’s facial features is matched to the CT/MRI data set to establish a common reference frame between the preoperative and intraoperative situations. The actual robot targeting guide location is computed from the 3D scan and compared to the predefined entry point and target location. 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 CranioAssist - MARS robot version for cranial applications and its controller; 2) custom robot mounting, targeting, and registration jigs; 3) an off-the shelf 3D laser scanner, and; 4) a standard computer. MARS is sterilizable a 5x5x7cm<sup>3</sup>, 150-gram six-degree-of-freedom parallel manipulator whose work volume is about 10cm<sup>3</sup> and whose accuracy is 0.1mm. It operates in semi-active mode; when locked, it is rigid and can withstand forces of a few kilograms. The adjustable robot mounting jig attaches the robot base to either the head immobilization frame or to skull-implanted pins (Fig. 1b-c). The computer receives the data from the robot controller, the 3D laser

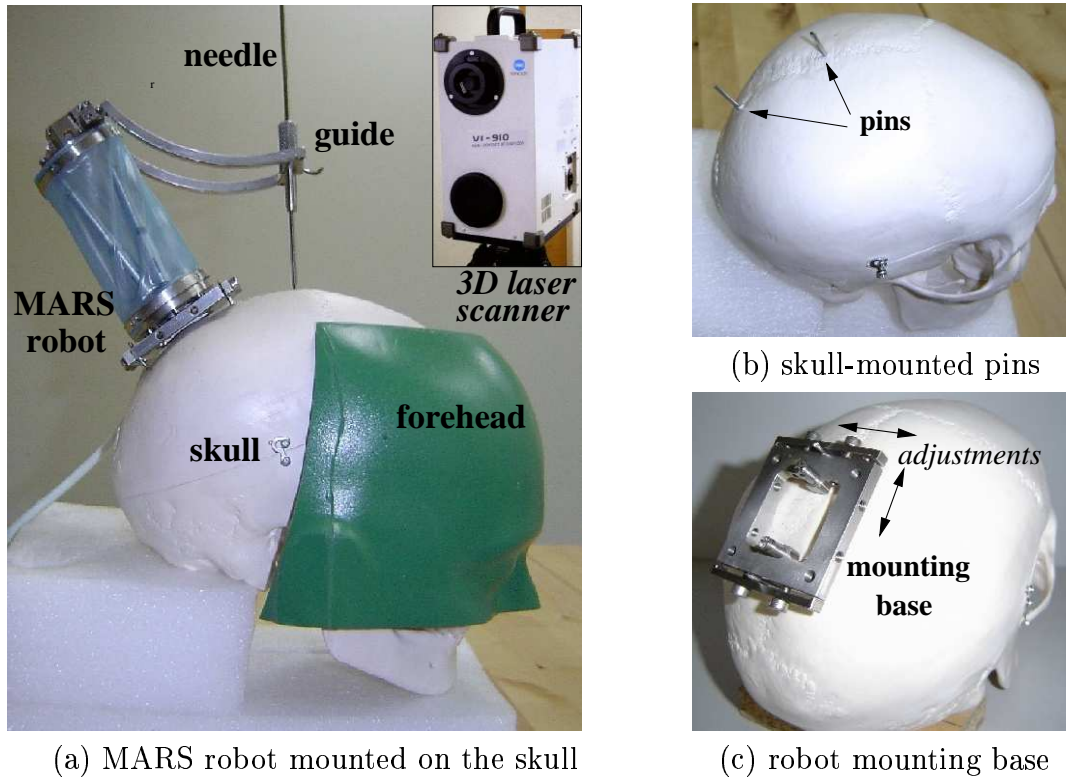


Figure 1. System concept: MARS robot mounted on the skull.

scanner, and the preoperative data set. The robot controller and the computer unit are housed in the same cart. The 3D laser scanner is mounted on a floor-standing tripod.

The system main software modules are: 1) preoperative planning; 2) 3D laser scan processing; 3) three-way registration, and 4) intraoperative execution. The preoperative planning module inputs the CT/MRI image and geometric models of the robot, its workvolume, and the mounting and targeting jigs. It supports the interactive visualization and manipulation of the CT/MRI data set and provides tools for defining needle trajectories consisting of entry and target points. Once the surgeon has defined the trajectories, the module automatically computes the robot placements so that the trajectories are at the center of the workvolume (both for skull and frame mounting). The surgeon can then visualize the planned intraoperative setup and adjust it to satisfy clinical criteria, such as avoiding placements near the cranial sinuses, temporal muscle, or emissary vein. The module automatically extracts the patient's face surface mesh and landmarks to be used for registration. The output includes the surgical plan (entry and target points), robot mounting mode and placement, and the patient face surface mesh and landmarks.

The 3D laser scan data processing module automatically extracts from the intraoperative 3D laser scan the registration jig and the relevant anatomical points: the face forefront and nose for frontal acquisitions, or the ear and nose for lateral acquisitions. The three-way registration module computes the transformations that establish a common reference frame between the preoperative CT/MRI, the robot pose, and the patient

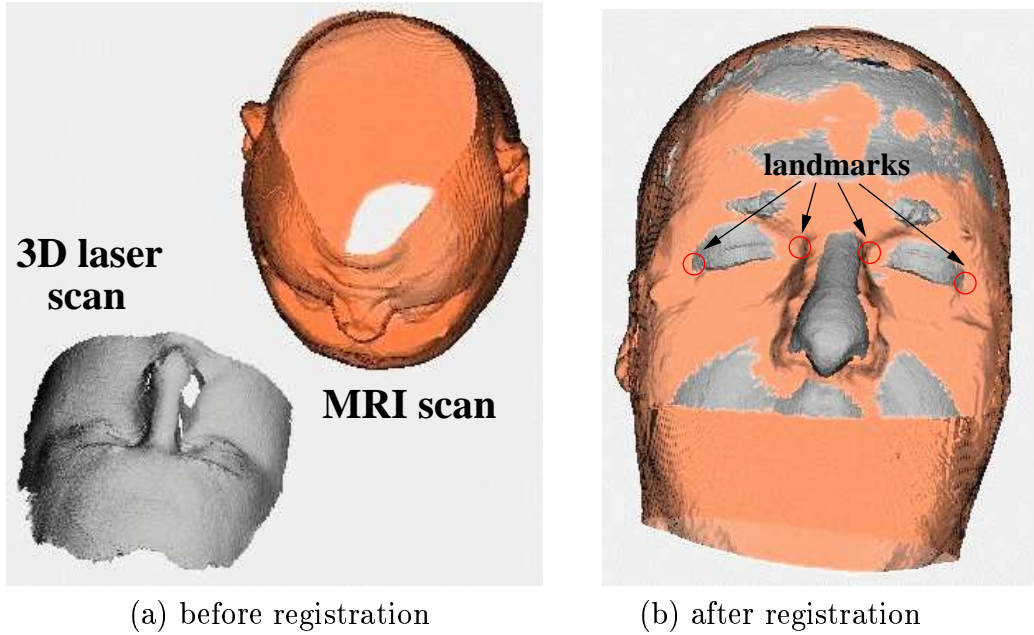


Figure 2. Laser scan to MRI registration.

skull. It proceeds in three steps. It first establishes a coarse correspondence based on 4-5 landmark points from the CT/MRI and the 3D laser scan, bringing the data sets to within a range of 5-10mm of each other. Next, it performs robust Iterative Closest Point (ICP) registration [13] between a subset of the 3D laser scan data and the CT/MRI surface points. Finally, the robot pose with respect to the preoperative plan is determined from this transformation and from the registration jig pose and robot geometry. The intraoperative execution module shows the surgeon the desired position of the robot and the planned trajectories as they are selected by the surgeon.

The surgical protocol is as follows. A preoperative CT/MRI scan of the patient is obtained without any markers or frame. Next, the surgeon visualizes the data and specifies, with the preoperative planning module, the desired entry points, target locations, and robot mounting type (skull or head clamp) and placement. Intraoperatively, the approximate robot placement is determined with the help of the intraoperative execution module. When the robot is mounted on the skull, two 4mm pins are implanted on the skull dura and the robot mounting base is attached to them. When mounted on the head frame, the robot base is attached to an adjustable mechanical arm afixed to the head clamp. Next, the robot with the registration jig is attached to the mounting base and one or more intraoperative 3D laser scans showing both the patient forehead and the registration jig are acquired. The system then automatically computes the offset between the actual and the desired robot pose with the laser scan processing and registration modules and positions and locks the robot in the desired configuration. The surgeon then replaces the registration jig with the targeting jig and inserts the desired instrument. On surgeon demand, the system automatically positions the robot for each or the predefined trajectories.

<b>LASER</b>	<i>Rested 1</i>	<i>Worried</i>	<i>Rested 2</i>
<b>MRI</b>	0.6m	0.6m	1.2m
<i>Worried, eyes closed</i>	1.06 (0.98)	0.93 (0.89)	1.11 (1.03)
<i>Relaxed, eyes open</i>	1.17 (1.16)	1.20 (1.17)	1.22 (1.21)
<i>Relaxed, eyes closed</i>	1.02 (1.00)	1.04 (1.10)	1.11 (1.10)

<b>LASER</b>	<i>Rested 1</i>	<i>Worried 1</i>	<i>Rested 2</i>	<i>Worried 2</i>	<i>Worried 3</i>
<b>MRI</b>	0.6m	0.6m, no chin	1.2m	1.2m	0.6m, chin
<i>Worried, eyes closed</i>	0.85 (0.72)	0.66 (0.57)	1.15 (1.12)	0.70 (0.65)	1.27 (1.22)
<i>Relaxed, eyes open</i>	0.69 (0.59)	0.71 (0.63)	0.72 (0.61)	0.93 (0.97)	1.15 (1.17)

Figure 3. MRI/laser scan registration error for 19 data set pairs of two patients. Columns indicate MRI scans and patient attitude (worried or relaxed, eyes closed or open). Rows indicate laser scans, attitude (worried or relaxed, eyes closed in all cases) and distance between the laser scanner and the patient’s face. Each entry shows the mean (standard deviation) surface registration error in millimeters. The overall RMS error is 0.99 mm (std=0.95mm) computed in 2.04 secs.

### 3. IMPLEMENTATION AND EXPERIMENTAL RESULTS

We implemented a prototype of the entire system, including the mounting, targeting, and registration jigs, and 3D laser scan processing and three-way registration modules.

To test the accuracy of the MRI/laser scan registration, we carried two experiments. In the first experiment, we obtained two sets of real MRI and CT data sets of the same patient and used the face surface CT data to simulate the laser scans. The MRI scans are  $256 \times 256 \times 80$  pixels<sup>3</sup> with voxel size of  $1.09 \times 1.09 \times 2.0$  mm<sup>3</sup> from which 300,000 face surface points are extracted. The CT scans are  $512 \times 512 \times 30$  pixels<sup>3</sup> with voxel size of  $0.68 \times 0.68 \times 1.0$  mm<sup>3</sup> from which 15,600 points from the forehead were uniformly sampled. The surface registration error, defined as the average RMS distance between the MRI and the CT surface data, is 0.98 mm (std=0.84mm) computed in 5.6 secs.

In the second experiment, we acquired several MRI and laser scans of the two student co-authors (R. Shamir and M. Freiman) with different facial expressions and pairwise registered them (Fig. 2). The MRI scans are  $256 \times 256 \times 200$  pixels<sup>3</sup> with voxel size of  $0.93 \times 0.93 \times 0.5$  mm<sup>3</sup> taken in about 6mins with the patient eyes closed from which 110,000 - 140,000 face surface points are extracted. Extracting the five landmark points for coarse registration took about 60 secs. The laser scans were obtained with a Konica Minolta Vivid 910 3D digitizer (USA) with a normal lens (f=14mm) in the recommended 0.6-1.2m range. They contain 35,000-50,000 points, obtained in 10-12 seconds with a manufacturer defined accuracy of 0.1mm or better. The data was lightly edited with the scanner software to eliminate the background. It was uniformly downsampled to obtain data sets of 1,600-3,000 points. Fig. 3 summarizes the results of the MRI/laser registration. For all 19 cases, the surface registration error is 0.99 mm (std=0.95mm) computed in 2.04 secs. No reduction of error was obtained with data sets of 3,000 points or more. These results compare very favorably with those obtained by Lueth et al [14].

#### 4. CONCLUSION

We have presented a system for keyhole neurosurgery that aims at overcoming the limitations of the existing solutions. It 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. Its novelty resides in its unique combination of a miniature robot and three-way contactless, anatomical registration between the preoperative data and the intraoperative situation based on 3D laser scan data.

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