Automatic Correction of Registration Errors in Surgical Navigation Systems

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Abstract— surgical navigation systems are used widely among all fields of modern medicine, including, but not limited to ENTand maxillofacial surgery. As a fundamental prerequisite for image-guided surgery, intraoperative registration, which maps image to patient coordinates, has been subject to many studies and developments. Medical scans such as Magnetic Resonance (MR) and computed tomography (CT) are currently common diagnostic tools in surgical applications. Typically information contained in these medical scans is neither in the coordinate system of the patient as positioned in the world, nor does it reflect the viewpoint of the surgeon during an operation. Any correspondences between the medical images and the actual patient environment have to be drawn mentally by the surgeon during the procedure. The approach of medical image registration and tracking seeks to compute these correspondences automatically and then directly augment the real operating environment with the information contained in medical scans. Such an environment provides the surgeon with an enhanced ability to plan, navigate and localize throughout a surgical procedure.

Key words: Surgical Navigation, Magnetic Resonance, Computed Tomography, Tracking, Optical Trackers

I. INTRODUCTION

Medical scans such as Magnetic Resonance (MR) and computed tomography (CT) are currently common diagnostic tools in surgical applications. Typically information contained in these medical scans is neither in the coordinate system of the patient as positioned in the world, nor does it reflect the view point of the surgeon operating on him. For instance, during an operation, the MR scan available to the surgeons is taken pre-operatively, and is viewed on a light-box on the wall of the OR. Any correspondences between the medical images and the actual patient environment have to be drawn mentally by the surgeon during the procedure. The approach of medical image registration and tracking seeks to compute these correspondences automatically and then directly augment the real operating environment with the information contained in medical scans. This allows the surgeon to view a patient and at the same time display in exact alignment with that view all desired internal structures, so that the surgeon in essence may \look inside" a patient before executing each stage in a surgical procedure. Our system also provides an interactive ability in which the surgeon can probe structures and points within the operating field and see a full 3D visualization of the corresponding points in the MR scan. By providing such registered visualizations, we hope to provide the surgeon with an enhanced ability to plan, navigate and localize throughout a surgical procedure.

II. RELATED WORK

Initial attempts to achieve image-guided neurosurgery consisted of stereotactic frames which directly provided the fiducials for registering the MRI or CT data to the patient. Stereotactic frames, though, are not only uncomfortable for the patient, but are cumbersome for the surgeon. They are limited to guidance along fixed paths and prevent access to some parts of the head. We would like to use a frameless system not only for its simplicity and generality, but also for its potential for use in other parts of the body. Frameless stereotaxy systems have been pursued by many groups, and usually consist of two components: registration and tracking.

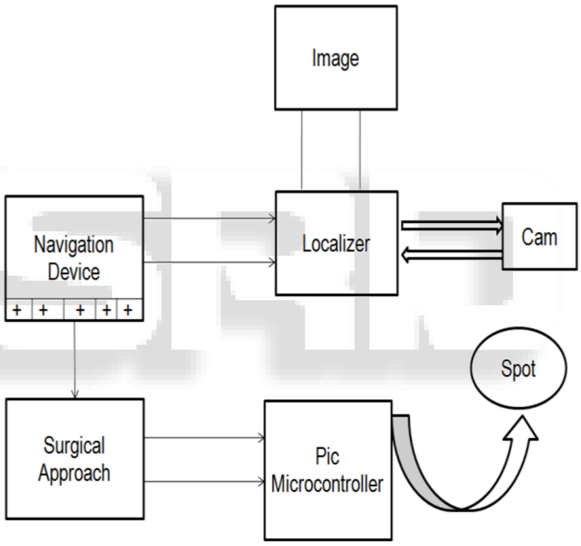

Fig. 1: General Block Diagram

A. *Patient-Scan Registration:*

Registration is the process by which the MRI or CT data is transformed to the coordinate frame of the patient. The two most common registration techniques for this application are fiducial-based and surface-based registration. A discussion of these methods follows below.

B. *Fiducial-Based Registration Systems:*

The most common form of registration uses fiducials either marker attached to the skin or bone prior to imaging or anatomically salient features 19 on the head. The fiducials are manually localized in either the MR or CT imagery and on the patient and the resulting correspondences are used to solve for the registration. Three such correspondences are required to solve the absolute orientation problem, but if more are used, then the best transformation (in the least squares sense) can be found using. Although this method is relatively simple, its users from some practical problems

III. SURFACE-BASED REGISTRATION SYSTEMS

Another registration approach is surface alignment in which the MRI skin surface is aligned with the patient's scalp surface in the operating room. Related surface-based registration approaches include. Surface-based techniques, while perhaps more complicated, provide more flexibility and are potentially much more accurate than fiducial-based methods. With this approach, no markers 20 need to be attached during the internal scan, whereas for a fiducial alignment, markers must remain attached between the time of scanning and the operation. This technique also uses information about the shape of the head and face to register, rather than simply basing the registration on a small number of correspondences. Surface-based techniques require a method of acquiring the location of points on the patient's scalp and an algorithm for computing the registration that best aligns those points to the MRI model skin surface.

A. Tracking:

Tracking is the process by which objects are dynamically localized in the patient's coordinate system. Of particular interest to us is the tracking of medical instruments and the patient's head. Common methods of tracking include articulated arms, optical tracking, passive systems, sonic digitizers and electro-magnetic localizers. Overviews and examples of these types of systems are described below.

B. Articulated Arm:

Articulated arms are attached to the head clamp or operating table and use encoders to accurately compute the angles of its joints and the resulting 3D position of its end point. The Radionics System (Burlington, MA) as well as the systems described in [28, 80] use an articulated arm to relate world positions to the corresponding locations

In an internal scan Such devices, though, may be bulky in the often crowded surgical field of the operating room. Furthermore, due to their mechanical nature, they may not be as fault tolerant as other tracking methods.

1) Light Emitting Diode-Based Localization:

Optical trackers use multiple cameras to triangulate the 3D location of flashing LEDs that may be mounted on any object to be tracked. Such devices are generally per received as the most accurate, efficient, and reliable localization system .Two such systems are the Flashpoint and Optotrak

2) Passive Tracking Systems:

Passive tracking systems use a video camera (or multiple video cameras) to localize markers that have been placed on instruments or objects to be tracked in the field. Such a system be ne ts from not requiring any type of umbilical or power cable attached to the instrument or object. The hand-held localizer has a certain pattern on it that is easily extracted from the two stereo images to accurately compute the position of the pointer tip.

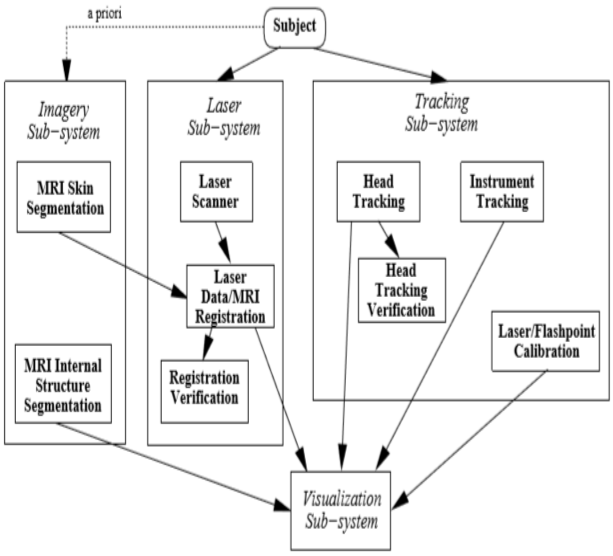

Fig. 2: Architecture of the Registration, Tracking, and Visualization System

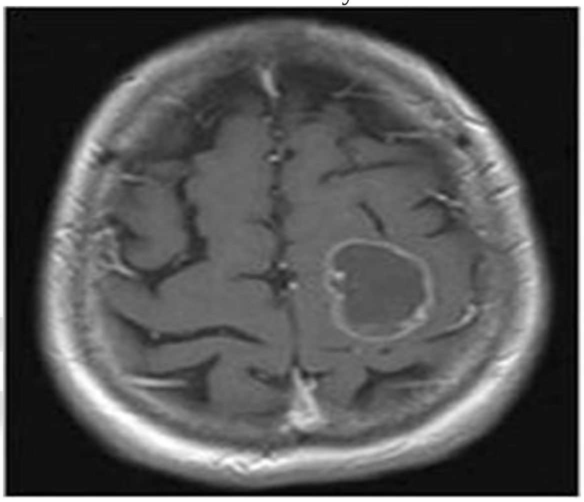

Fig. 3: MRI Image of Brain

Possible sources of error in our system include

- Imaging and segmentation errors,
- Errors localizing the Flashpoint probe,
- Errors in laser scanning,
- Registration errors,
- Untracked rigid motion of the patient,
- Brain shift

IV. IMAGING AND SEGMENTATION ERRORS

We do not account for errors during the imaging and segmentation process, but take steps to minimize these errors and assume, based on experience, that the errors are negligible. The resolution of the MR images affects the accuracy of the segmentation and registration. The protocol we use generates an image with a voxel size of 0:9375mm 0:9375mm 1:5mm. Imaging artifacts, especially those caused by patient motion, can introduce errors. To minimize patient motion during scanning, the patient's head is comfortably restrained with pillows while in the scanner. A piece of tape across the head is also used, not so much as a restraint, but as a reminder for the patient to remain still during the acquisition. If motion blur is detected in the resulting scan, then the patient can be re-scanned to improve accuracy.

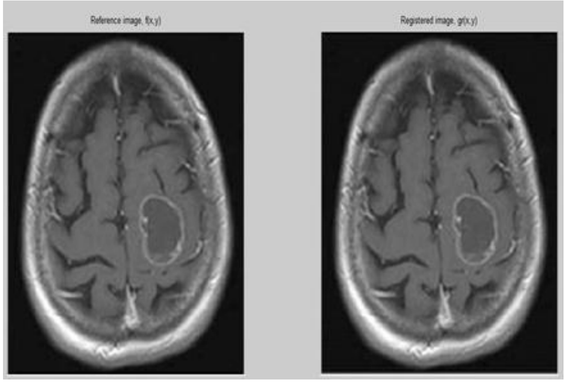

Fig. 4: Segmentation Error

V. DIGITIZER ERRORS

Our system uses two devices to acquire 3Dpositional information in the world. The first is a highly accurate optical localizing system from Image Guided Technologies called the Flashpoint 5000. This device tracks LEDs that can be placed on probes or reference frames. Details our how our system uses the devices are discussed . Our Flashpoint device was calibrated and tested at the factory before we received it. The mean error of localizing an LED was calculated to be 0:22mm with a standard deviation of 0:26mm. The maximum error found during the calibration tests was 0:87mm. The probes that we use may have slightly more error, given that the point of interest (the tip of the probe) is some distance from the two LEDs used to localize it. However, the error is still well within a millimeter on average.

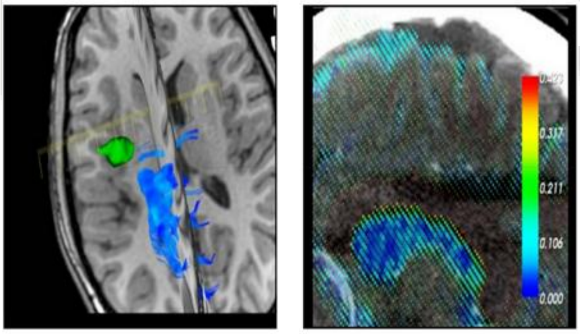

Fig. 5: Spotting the Affected Part and Detecting the Digitizer Error

VI. REGISTRATION ERRORS

The registration process is the component of the system that is most difficult to prove correct, given its complexity. These investigations highlight the conditions under which the registration will most likely succeed, and also the break-down point of the algorithm as a function of lack of salient structure or excessive measurement noise. In our experience, the registration algorithm has performed very well and is robust to measurement noise, outliers, and local minimum. One time when the registration failed to converge was the first time that our system was brought into the operating room. The resident had sterilized and draped the patient before we had the opportunity to acquire skin points and perform the registration. Only a very small region of the forehead and cheeks were visible through the draping. In this case, we could not perform a registration due to the lack of coverage of the registration points.

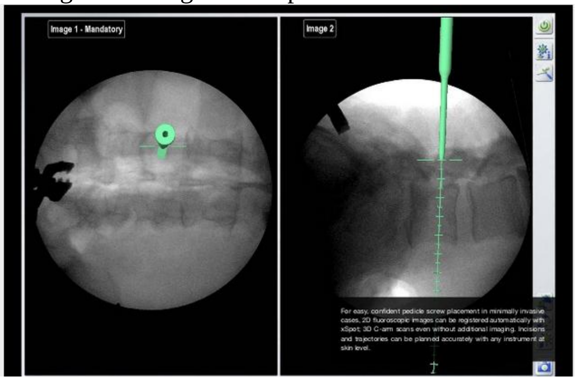

Fig. 6: Registration Error

VII. UNTRACKED MOTION ERRORS

We currently have two methods of tracking patient motion during surgery: suturing LEDs to the skin and attaching LEDs to the clamp. However, we do not account for the motion of the skull relative to our LEDs, as the skin or clamp could move relative to the skull. Depending on the shape, size, and position of the skin surrounding the flap may or may not be stable enough to be used as the reference frame. In cases where the flap is small or C-shaped and the LEDs can be placed a few centimeters from the opening, we have found this tracking method to be acceptable. However, when the skin opening is large or when the skull is exposed by pulling the skin flaps apart, tracking the skin would introduce large errors in the registration. Due to this dependence on the incision, we have found tracking the clamp to be a more reliable option. We now only suture LED to the skin in cases where a Mayfield clamp is not used, which is relatively uncommon. In most cases, we attach a device with three LEDs to the May field clamp to track the motion of the patient

VIII. CONCLUSION

This thesis describes a registration, tracking and visualization system for image guided surgery. The system was designed to provide surgeons and clinicians with a set of useful tools to assist them during preoperative and intraoperative procedures, by making better use of the information contained in internal scans. The system has been used for such applications as neurosurgical navigation, transcranial magnetic stimulation, and image-guided endoscopic intubation.

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