EPI-GUIDE: Towards a Disposable, Low-Cost Guide for Freehand Ultrasound Support During Epidural Procedures

Abstract

It is well known that the performance and safety of epidural anaesthesia can be enhanced through the use of ultrasound imaging. However, in practice, the use of ultrasound by a sole clinician can be complicated as one has to attend to both an imaging and an anaesthetic procedure concurrently and quickly. Towards this, we introduce a prototype disposable guide with integrated non-contact pose estimation to support freehand ultrasound reconstruction. This system is evaluated ex vivo on a lumbar spinal phantoms embedded in gel with the measured motions used to produced a direct voxel reconstruction. This provides a hands-free interface that has been subsequently evaluated with several users.

1 Introduction

Needle placement is one of the most common surgical tasks. Incorrect placement can have harmful consequences. A case in point is epidural anaesthesia, where a relatively large needle incorrectly inserted can cause damage to nerves, the spinal cord and local soft tissue. Successful insertion relies on the skill of the clinician. Typically, this is performed by manually using palpitation and/or initial 2D ultrasound imaging to find landmarks following by tactile guidance to target the needle to the epidural cavity [Rafii-Tari et al., 2011].

There is evidence to show that imaging can help [Karmakar et al., 2009; Marhofer et al., 2005]; in fact recent guidelines [NICE, 2008] have advocated the use of ultrasound imaging to assist clinicians steer the needle. This has gone someway to improving outcomes. There are many issues including: image analysis for interpreting the 2D images [Souzdalnitski et al., 2011]; shifting focus shifting (from the needle to the spinal column); and logistical (i.e., one needs to attend to both an imaging and an anaesthetic procedure concurrently).

With an eye on the latter, the paper introduces a low-cost, disposable epidural assistance tool, which we term the “EPI-GUIDE” or “EPIdural Guidance using Ultrasound Influenced Directional Enhancement” system (shown in Fig. 1). It consists of an instrumented mechanical support for a (2D) ultrasound transceiver that subsequently supports a freehand ultrasound reconstruction allowing for the production of an augmented 3D image from the gathered set of 2D image slices.

Figure 1: EPI-GUIDE (EPIdural Guidance using Ultrasound Influenced Directional Enhancement system) Prototype. This low-cost guide measures probe orientation relative to surface allowing for direct image alignment.

In this way, the system relieves the operator from continual manipulation of the ultrasound probe for navigation by essentially acting as a third hand. It also reduces context shifting (and procedural time required) by allowing for the overlaying of multiple ultrasound images relative to probe adjustments.

Additionally, to keep the probe simple, disposable, (and low-cost), the design takes exploits a common feature of epidural procedures that a sweeping or rotational motion is
more often used than translational one [NICE, 2008; Kar-
makar et al., 2009]. In this the guide constrains the motion
to one (yaw) degree of freedom, considerably simplifying the
motion measurement to that of a precision encoder.

This paper introduces the concept of a low-cost, disposable
epidural assistance tool. A brief background on the use of ul-
trasound to support epidural anaesthesia is given in Section 2.
Section 3 presents the design of the EPI-GUIDE as based on a
small, magnetic pole-based precision encoder circuit. Initial
ex vivo trials from this unit are presented in Section 4. The
paper concludes with some considerations on the current de-
sign and areas for future work from both a clincial workflow
and robotics interaction perspective.

2 Background
Surveys of epidural anaesthesia success rates are abundant
and cover many patient subgroups and operator skill levels.
Failure rates and complications such as dural puncture and
nerve trauma are recognized and published in many surveys
[Dickson and Jenkins, 1994; Horlocker and Wedel, 2000;
Riley and Papsin, 2002; Tortosa et al., 2003]. Depending
on the indication, patient state and operator skill, failure rates
vary from 5.7 to 38%. One of the shortcomings indicated by
these works is the need to superimpose imagery so as to “see”
where the target (and needle) are located.

2.1 Assisting Epidural Anaesthesia
Epidural anaesthesia is based on insertion of a hollow needle,
and thereby a catheter, to the epidural space which exists be-
tween the ligamentum flavum and the dura mater enveloping
the spinal cord. Clearly when the procedure is conducted on
a conscious subject it is distressing, in some cases painful and
is often required to be performed quickly. Anatomical land-
marks on the surface are traditionally studied and located be-
fore insertion of the purpose designed needle (Touhy needle)
under local anaesthesia [Reynolds, 2001].This is performed
using the physical force feedback from the tissues encoun-
tered as guidance. A loss-of-resistance after penetration of
the ligamentum flavum is a common marker the key indica-
tor of reaching of the desired target. Apart from the initial
anatomical landmarks, the procedure is visually blind for the
clinician. The technical challenges of obesity, concomitant
medical problems and disrupted anatomy due to spinal dis-
ease are contributors to the significant failure rates for this
popular procedure.

2.2 Freehand Ultrasound
Although real-time 3D, B-mode ultrasound imaging systems
are commercially available, the complexity, cost and limited
utility in general theatre environments has limited their up-
take. 2D ultrasound imaging systems, on the other hand are
ubiquitous in most environments where epidural anaesthe-
sia is performed. This is particularly true for delivery suites
where antenatal care is dependent on assessment of the foetus
using ultrasound.

Towards this freehand ultrasound (see also Fig. 2) is a
mechanism to obtain a 3D visualisation of the spine incor-
porating the epidural space targeted by the clinician requires
the acquisition of multiple 2D slices which can be aligned to
form a 3D volume [Treece et al., 2003; Doctor et al., 2008].
Such a simplistic approach has several technical problems.
Firstly, the 2D slice must represent image information from a
different viewpoint or different viewing angle. Secondly, the
probe must therefore be moved or undergo an angular dis-
placement and this translation must be accurately measured
in order to re-assemble the 2D slices appropriately.
An imaging-only approach to estimating this motion has been proposed by which the images are correlated using the speckle noise of overlapping portions of neighbouring images [Dickson and Jenkins, 1994]. This approach, while “free-hand,” does not allow for arbitrary motion as it is very sensitive to changes in probe rotation [Riley and Papasin, 2002] and contact pressure. Even with careful motion, the process can be slow due to the limited overlap between images and extensive computation needed [Horlocker and Wedel, 2000].

Instead, a more direct measurement of pose is adopted, such as is seen in the Freehand project [Boctor et al., 2008] in which the synthesized 3D ultrasound is produced by tracking the rotation and translation of the probe between images [Tortosa et al., 2003]. This process requires instrumentation and can introduce another level of complexity as the often noisy sensor signal requires processing before it can be used to guide the synthesis of the 3D volume or the use of external tracking systems (e.g., NDI Polaris or NaturalPoint OptiTrack systems) that would require the procedures to be held in a location with the cameras and for markers to be added to the transducer.

2.3 Supports and Guides

Many approaches have been proposed to augment the information flow around an ultrasound transducer ranging from auditory alerts to haptic interfaces to augmented displays [Yaniv and Cleary, 2006]. While many tend to be large and risk impeding an anesthesiologist’s work-flow, there are portable systems, such as the Sonic Flashlight, that provide guidance relieve the clinician from having to look away to a screen and thus saving the context switching [Chang et al., 2005; Wang et al., 2009]. However, these systems (in general) do not provide freehand reconstruction. Additionally, these system are still complex and not low-cost or disposable.

Towards this, snap-on needle guides by simplify ultrasound-guided injections by attaching the needle to the probe [CIVCO, 2013]. However, the probe is still held by the physician and these are limiting as the angle of the needle relative to the probe is fixed. Several variations of probe holders exist, such as one designed by Kato et al. [Kato et al., 2013]. However, these are fixed to a stand and do not provide feedback on the probes angular position.

3 Design

3.1 Disposable, Instrumented Ultrasound Guide

The mechanical design is shown in Fig. 3(a). For prototyping, the parts were fabricated using a 3D printer. The probe snaps into the probe bracket, which is attached to the base. As the axis of rotation is located at the skin surface, it would be difficult to fit conventional rotary encoders. Therefore, a linear magnetic encoder is used instead.

Pose detection is performed by converting linear displacement measurements made by the encoder (a AS5304, see also Fig. 3(b)). This uses a magnetic strip which is mounted above the arch of the base (Fig. 3(a)). The magnetic strip has a pole pair length of 4.0 mm. By interpolating between four linear analog Hall sensors, the AS5304 outputs 160 steps per pole pair, therefore it has a resolution of 25 microns (µm).

Finally, communication is performed using a AS5304 that has been programmed to emulate pulse trains like a typical encoder. The steps are counted on an Atmel ATtiny85 microcontroller. The ATtiny85 is connected to a FTDI chip, FT232RL, which then outputs data on a USB-mini port. When a request is sent from a connected computer to the circuit board, the number of steps counted since the last request is return to the computer and the counter is reset.

3.2 Visualization

The process of freehand ultrasound visualization is based on a measurement the motion and alignment of the 2D image (planes) taken. This is illustrated in Fig. 2.

The freehand ultrasound visualization for each voxel finds the closest point on each of the image planes, then selects the closest two of those and linearly interpolates between the two pixel values to determine the voxel color. The transparency of the voxel is also set to the pixel’s luminance value (i.e., completely black pixels are transparent and white pixels are solid).
4 Evaluation

The approach relies on the location and rotation of the probe being accurately measured using an alignment frame with the ultrasound probe guide the acquired image will be directly embedded into the 3D reconstruction grid using simple (e.g. linear) interpolation methods in order to occupy the corresponding space in the reconstructed volume.

Figure 4: A 1:1 lumbar spinal model in gel for testing the guide and reconstruction

This was tested with a 1:1 lumbar spinal model (see also Fig. 4). A continuous image stream from a commercial ultrasound unit (a GE Logiq 8L) was tested in a laboratory with an operator simply maintaining the probe in contact with the phantom (spine embedded in gel). As noted the volume is then reconstructed using a geometric process tools. A sample result is given in Fig. 5).

5 Conclusions and Future Work

The EPI-GUIDE illustrates the mechatronics principles necessary for a low-cost instrumented approach to freehand ultrasound to support epidural anaesthesia. The prototype system brings together instrumentation of the ultrasound probe; synthesis of 3D image volumes from 2D ultrasound images; and a hands-free user interface.

Future work will consider hardware usability improvements based on the current analysis. For the the registration it will look at reconstructing this using non-linear optimisation tools (e.g. interior-point optimisation methods). An on-probe inertial measurement unit (IMU) may be added to estimate the probe position after initial alignment. Different levels of accuracy of location information will be investigated. This leads to a disposable guidance system as illustrated if Fig. 6.

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Figure 6: EPI-GUIDE as part of an Integrated System: Here 2D slices from a clinician-swept ultrasound probe form the origins of the 3D augmented image volume. A target region may then be identified and marked within the 3D image.
Figure 5: A sample reconstruction of rotary displacement from the EPI-GUIDE
References


