American Journal of Biomedical Engineering 2013, 3(6): 169-174
DOI: 10.5923/j.ajbe.20130306.05

A Mobile Augmented Reality Application for Image Guidance of Neurosurgical Interventions

Matt Kramers[1,2,*], Ryan Armstrong[1], Saeed M. Bakhshmand[1], Aaron Fenster[1,2], Sandrine de Ribaupierre[1,3,4], Roy Eagleson[1,4]

[1]Biomedical Engineering Graduate Program, University of Western Ontario, London, N6A3K7, Canada
[2]Robarts Research Institute, University of Western Ontario, London, N6A3K7, Canada
[3]Department of Clinical Neurological Sciences, University of Western Ontario, London, N6A3K7, Canada
[4]Department of Electrical and Computer Engineering, University of Western Ontario, London, N6A3K7, Canada

Abstract Image guidance for complex surgical procedures is gaining popularity within operating rooms. Providing the appropriate contextual information to aid in navigation can reduce cognitive load on surgeons, thus reducing surgical error. To date, clinical implementations of image guidance have required extensive equipment, setup and technical expertise to operate precluding their use when treating acute conditions in the intensive care unit. We present an application targeted at mobile platforms that utilizes augmented reality and image-based tracking in order to add preoperative contextual information to neurosurgical procedures, specifically spatial information. A pilot evaluation was performed to examine accuracy of the system. Initial results show increased accuracy for a targeting task with the aid of the visualization.

Keywords Image Guidance, Augmented Reality, Neurosurgery, Graphics, Segmentation

1. Introduction

Placing an external ventricular drain (EVD) is a fundamental neurosurgical procedure performed to treat acute hydrocephalus – a condition characterized by an accumulation of cerebrospinal fluid within the ventricular system, either due to obstruction or by a problem of reabsorption[1, 2]. The procedure consists of drilling a burr-hole in the skull, followed by a bling placement of an external ventricular drain using external landmarks for guidance. This procedure allows drainage of cerebrospinal fluid to relieve intracranial pressure. While most neurosurgical interventions are usually performed in an operating room (OR) while the patient is under sedation[3], this is rarely the case for this procedure. Since the insertion of an EVD is usually performed on critically ill patients (either for acute hydrocephalus or after a trauma), the predominant difficulty involves transportation of the patient[4] mostly due to life-support equipment[5]. To accommodate such a scenario, manual operation of mobile drills for burr-hole trephine can be performed within the Intensive Care Unit or in the Emergency room. While advantageous in avoiding the difficulties in relocation to the OR, this technique precludes the use of certain immobile equipment present within the OR.

While external ventricular drain placements are among the most common and basic of neurosurgical procedures, they are generally performed free-hand, relying on surface landmarks on the patient as well as the spatial reasoning of the operating surgeon to determine optimal trajectory of tools within the complex workspace. While it might be relatively easy to target large ventricles placed in a normal anatomical position, most patients will have small ventricles with some anatomical variation, possibly displaced by lesions occurring after the trauma. As a result of navigational error due to free-hand placement, a number of complications can occur, including malposition, non-function, infection and haemorrhage[6]. While neurosurgeons generally consider the manual procedure to be safe, a number of studies have identified the technique as suboptimal[7, 8, 9]. In addition, this procedure is often performed by junior residents who are on-call. Indeed, many of these complications are a result navigational error, often requiring repositioning of the EVD into the ventricular system. In addition to the complications resulting from such misplacements, the procedure time is increased and additional, unnecessary tissue damage occurs.

The goal of this project was to create a neurosurgical guidance system to aid in visualization of the ventricles in order to perform the procedure less blindly. This was achieved through the use of an augmented reality (AR) viewport to provide inner anatomical context to the surgeon during navigation. As CT scans are standard for such

* Corresponding author:
mattkramers@gmail.com (Matt Kramers)
Published online at http://journal.sapub.org/ajbe

procedures, our system relies on preoperative CT imaging volumes for extraction of spatial information, particularly the ventricular system which is trivially isolatable from CT images. Since performing the procedure in the OR may not always be feasible, an additional design constraint on the system was mobility. This constraint prohibits the use of many clinical tracking systems that require the incorporation into integrated, stationary platforms.

2. Related Work

According to the literature, tracking of an object's position is the main aspect which influences accuracy of a system and determines the level of interference with the medical workflow. The majority of AR systems take advantage of Head Mounted Displays (HMD), hand-held or fixed displays to show computer generated scenes to the user. Visualization techniques are used to incorporate preoperative medical images during the intervention as 3D objects rendered in real-time. Considering these three methods of AR, we can classify some recent work and indicate their advantages and deficiencies.

As an early prototype, in 1968 Sutherland et al.[10] developed a mechanical tracking system for their HMD 3D display. It was realized by attaching a mechanical linkage to the HMD which measured head position by computing axial displacement of the joints of a passive robotic arm. In similar work in 1992, Bajura et al.[11] replaced the mechanical linkage with electromagnetic sensors to determine the pose of a HMD and an ultrasound probe. Measuring position remotely (by magnetic or optical tracking systems) leads to a significant improvement in terms usability of the system, since they give more freedom to move the HMD within the operation site. Shamir et al.[12] used magnetic trackers and point based registration to align images, risk surfaces and segmented models to physical head models. In further work, Shamir et al. utilized the ability to track multiple objects simultaneously using optical tracking to develop an AR probe that incorporated a camera attached to a reference plate[13]. The output of the system was an augmented video image of the therapeutic site with relevant superimposed graphical content rendered according to the position of the probe. HMDs interfere with medical work flow and may restrict a surgeon's natural movement. As a result, hand held displays and cameras (AR probe as an example) are becoming more feasible within the operating room. DEX-ray [14] is a miniaturized version of a hand held probe with an integrated video camera. Naturally, in[13] and[14], displays are fixed at some point in operation room and a surgeon is required to switch between the real scene and the displayed AR scene, and thus increases the system's complexity. Mischkowski et al. found that camera and display units could be combined, as demonstrated by their X-scope[15]. X-Scope could be used for detection of bony segments in real-time and results were displayed on a hand held LCD. This configuration resembles current mobile devices. Infrared optical tracking became feasible by attaching reflective frames to portable display devices. These mobile devices enable surgeons to inspect patients from different points of view. In contrast, optical trackers impose limitations on this procedure, due to their limited workspace, necessity of attaching multiple reflectors to objects of interest and line of sight issues. An alternative method for tracking utilizes image-based tracking algorithms, which require adequate speed and accuracy. Fisher et al. developed a hybrid tracking scheme to calculate final estimation of the pose in an AR framework for a neurosurgical application[16]. Two streams of sensory data (Infrared and vision based tracking results) are combined by a pose estimation algorithm based on RANSAC (RANdom SAmple Consensus) which is an iterative parameter estimation algorithm. Simulations of this work were performed on an artificially textured cube as a reference model.

3. Methods

For an AR system to be useful in a clinical context, it must be readily available and not provide a significant change to the existing workflow[17]. It is therefore important that the pre-processing required to prepare and segment medical images for use in AR systems is relatively rapid and uncomplicated[18]. Additionally, for our application to be suitable for use in the intensive care unit, it must be portable and requiring minimal setup. These are all of the requirements that affect the design of our system. In section 3.1 we discuss the use of image-based tracking through the Vuforia software development kit. In section 3.2, the design and implementation of the pipeline for importing patient-specific data is described. Section 3.3 covers the user interface design and section 3.4 describes our pilot evaluation of system accuracy.

3.1. Vuforia and Augmented Reality Implementation

AR can provide users with additional visuospatial context by overlaying anatomical images on the head of the patient. This can be beneficial to surgical planning and navigation by offering additional contextual information to a procedure through incorporation of preoperative medical imaging data. This gives surgeons the ability to not only view patient anatomy extracted from medical images, but to do so with spatial context relevant to the tasks performed during the procedure. Ventriculostomies require surgeons to estimate entry points and trajectory paths relying on preoperative medical images and experience. Our AR tool allows surgeons to visualize – using a mobile device as a viewport - the location of internal anatomical features projected onto the patient. This provides the surgeon with additional contextual information to aid in navigational tasks with the intent of increasing accuracy compared to blind navigation.

The implementation of our application included the use of an AR software development kit, Vuforia, developed by Qualcomm[19]. The essential requirement of our system was the ability to register the three-dimensional virtual image-space to the physical world's three-dimensional space utilizing image-based marker tracking through a single on-board device camera. Qualcomm delivers an API capable of tracking multiple planar images using the mobile device's camera. For our application we constructed a 40mm x 60 mm x 80 mm rectangular cuboid shaped tracking object and printed unique, feature-rich, images on each of its six faces. Using Vuforia's API, the approximate pose of each of the detectable image faces were averaged and used as an approximate pose transformation for the entire tracker geometry. The tracker was attached to a pair of safety glasses that would be placed on the patient, as illustrated in Figure 1. We made the assumption that when the glasses rested on the patients head, they will rest directly on the nasion – the region between the frontal bone of the skull and nasal bones, which is easily discernable in CT images and exhibits high reproducibility among experts[20]. In this case, the tracker would be 5mm anterior to the patient's nasion, providing a landmark relative to the tracker. Using OpenGL ES, surface representations of the patient's segmented anatomy extracted from the CT images could be then be displayed to the user through the device's viewport.

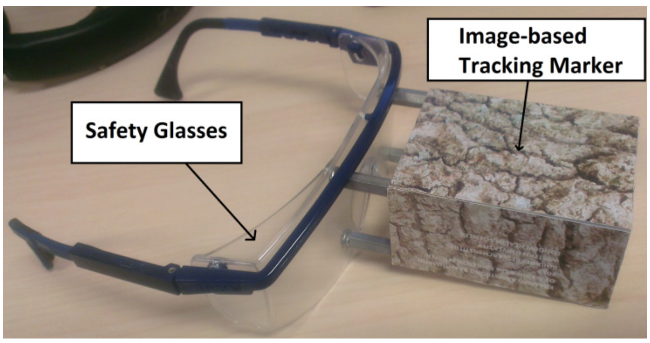

Figure 1. Tracking marker fixed to safety glasses for patient head pose estimation and registration of anatomy to scene

An additional feature that was implemented was a second tracking device that could be used as a stylus within the augmented environment. This enables the user to view entry point trajectories with respect to the projected anatomy. In addition, this feature may provide cues to improve the user's depth perception by providing interaction with the objects in the scene. To achieve this, we rendered a virtual beam that emitted outwards from the pointing device towards the patient's head. This feature is depicted in Figure 2.

The ability for a user to perceive the augmented surface graphics and gain contextual knowledge from the device depends on its ability to render graphics with appropriate visual cues for perceiving depth from 2D images. The skull surface, generated during the segmentation process, is used in the visualization with controlled blending to give the effect of being semi-transparent as the user views a patient's head through the device. By combining this visual element, texturing, shading, perspective projection, as well the pointing stylus, an adequate viewport for ventricle navigation can be achieved.

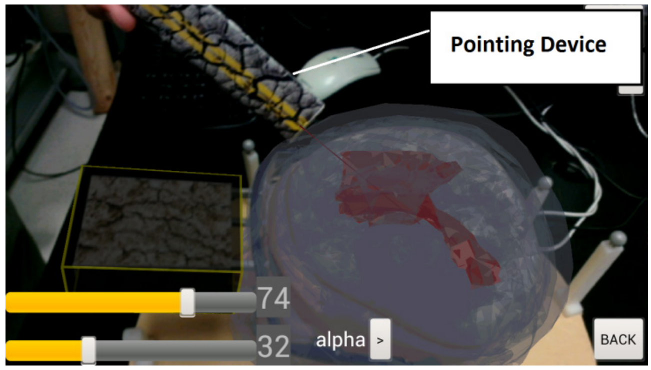

Figure 2. The tracked pointing device provides visual feedback for planning entry point locations and trajectories. The device also allows for additional interaction between the user and the AR scene

3.2. Segmentation and Registration of Patient Data

In order to portray the internal anatomy of the patient overlaid in the scene, the anatomy of interest must first be segmented and registered into the scene. For these tasks, we have developed a custom interface to guide the user through such content creation. The software pipeline is modeled as a wizard-style application that runs the user through the stages required to create all of the content, prompting for appropriate input when required. As we are targeting a neurosurgical procedure that is performed as an emergency, CT images will primarily be the imaging modality of choice preoperatively and thus, will serve as the input to our pipeline (contrasting with MR images that are done when the patient is stable). There are two anatomical features that are essential in our guidance system: the lateral ventricles to guide proper positioning of the EVD, and the outer skin of the head to visually verify alignment of the virtual and physical scenes. The outer skin segmentation can be performed automatically by selecting the entire outer boundary voxels of the input image. Segmentation of the lateral ventricles is less trivial due to strong inter-patient variation that occurs as a result of hydrocephalus and/or head trauma, as well as artifacts inherent to the preoperative images such as image noise, intensity inhomogeneity, low contrast and the resulting partial-volume effect. While there are automatic algorithms for segmentation of the lateral ventricles from CT images[21, 22, 23], the majority of these rely on prototypical model priors and are not robust when dealing with strong anatomical variations in the ventricular system. Additionally, while numerous segmentation platforms exist for semi-automatic extraction of features[24, 25], such platforms require algorithmic domain knowledge to achieve appropriate segmentations by fine-tuning parameters of the algorithm. As such, we have developed our pipeline as a standalone platform for ease of use by non-experts. In order to achieve an optimal balance of pipeline efficiency and segmentation accuracy, our approach employs a semi-automatic algorithm that relies on user knowledge and interaction. A recent survey[26] of semi-automatic techniques applied to segmentation of hydrocephalic ventricles indicated that the level set approach[27] was most effective compared to random walk [28] and min-cut/max-flow[29] algorithms. For maximum user efficiency, the level set algorithm is incorporated in our pipeline with the addition of a knowledge-based region growing approach for initiation. Initially, the user must select two rectangular regions that correspond to each lateral ventricle, allowing placement of initial region growing seed points in image space as well as determination of image characteristics, such as noise. This allows fine-tuning of the algorithms without user intervention. When the segmentation of both lateral ventricles is complete, they are merged as we are only concerned about the general spatial features of the lateral ventricles, so leakage between them is of no concern.

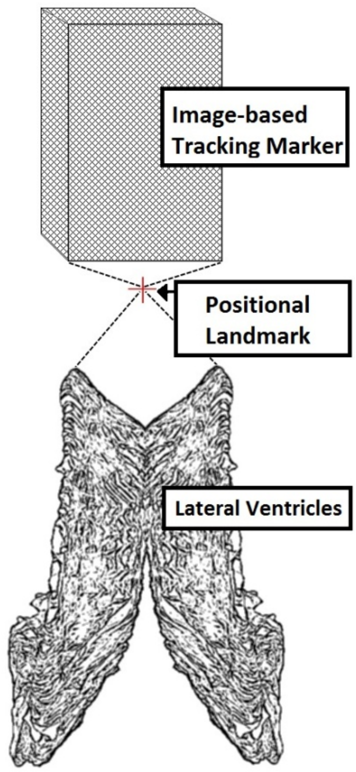

Figure 3. Anatomy segmented from preoperative images aligns with the physical tracker and is positioned using the nasion as a positional landmark

After the segmentation, the user must verify that the ventricles were correctly segmented by examining either the raw image slices with the segmentation overlaid, or a volumetric rendering of the ventricles. The volumetric rendering module was developed to aid in quick verification of segmentation by emphasizing strong variations in intensity values of the segmented region, which are generally indicative of a region growing leak. When the user is satisfied with a given segmentation, a marching cubes[30] algorithm is performed on the volume and meshes of the ventricles and head are extracted. These meshes are further smoothed and decimated to achieve suitable performance on mobile devices. The amount of decimation will depend on the amount of video memory available.

Once the segmentation is complete, the coordinate system of the image space must be registered to the application's virtual space to ensure proper correspondence between the rendered ventricles in the display with the patient's head. To simplify this process, we make the assumption that the rectangular prism image-based marker is aligned perfectly with the patient's head. With orientation known, only position and scale of the anatomy must be determined. Scale is determined by saving a mapping from image space (where voxel millimeter spacing is known) to virtual space in relation to vertices in the scene. The relation of physical space to virtual space is determined by the tracking system since the dimensions of the image-based marker are known. This allows proper scaling of the anatomy. Position is determined by prompting the user to select the point in the initial CT image that corresponds to the nasion. From the nasion, we know the distance to the center point on the attached side of the marker, allowing positioning of the anatomy at the appropriate location. The registration is depicted in Figure 3.

3.3. User Controlled Registration Correction

Although the segmented surfaces were registered to several points on the patients head chosen during segmentation, an accurate placement of the tracking glasses cannot always be achievable. This can be caused by a number of factors, such as nose and head shape variations. For this reason, a user interface was developed to allow users to make adjustments to the alignment of the physical and virtual scenes. The user is able to manipulate the pose of the virtual space through translation, rotation and scaling controls using the skull as a reference as it is superimposed over the view of the patients head. This is illustrated in Figure 4. This allows the surgeon to visually correct misalignment due to improper or abnormal placement of the head-mounted marker or inaccurate placement of landmarks during scene generation.

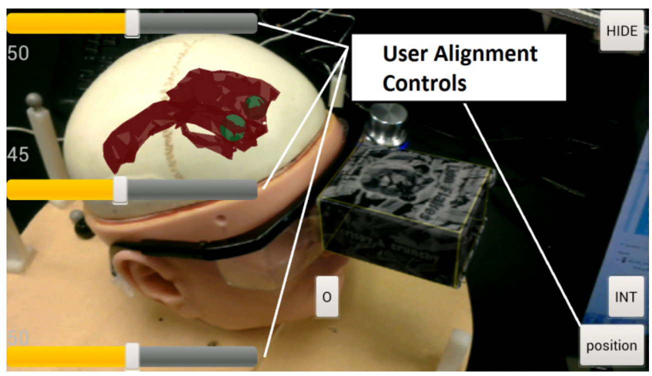

Figure 4. Users have access to multiple sliders and buttons to manually adjust the virtual models to achieve appropriate alignment of anatomy, as well as visual settings that aid in guidance

3.4. Evaluation of System Accuracy

To evaluate the accuracy of our system, we performed a pilot study to quantify accuracy of the system applied to an environment of similar scale to the implementation. Our evaluation focused on system accuracy rather than user performance which will be evaluated in future work.

Accuracy was assessed by having users target corners of two-dimensional shapes projected onto a plane with known coordinates. A sheet of paper represented the plane in physical space, which was registered to the virtual plane. Rectangles and triangles were used as the shapes projected onto the plane as they offer clearly distinguishable corners for localization. The shapes were rendered transparently as to not impede the localization of points by the user.

As this is a pilot study to initially assess system accuracy, the study was limited to two users performing targeting tasks. The tasks required the user to place markers at the location that they perceived as the corners of the shapes as they were displayed to them. In addition, the virtual plane with targets was displayed on an external monitor so that the user had exposure to the position and shape of each target, prior to and during the targeting task. Since only accuracy was being evaluated, no constraints on time were imposed. The tasks were performed on a total of 10 shapes per user, with half of the tasks being guided by our augmented reality device, while the remaining tasks required users to rely only on the external monitor for reference. Analysis involved examining the deviation of the points on the physical plane placed by the user to their known positions on the plane in the virtual space.

4. Results

The Euclidean distance between each of the users' points and the virtual targets were calculated to determine targeting error. With AR guidance, the mean error for targeting was 9.88 ± 5.34 mm over a total of 35 individual points. When users did not have AR guidance, the mean error rose to 13.03 ± 6.15 mm, again over 35 individual points. To test the significance of this result, a Student's t-test was performed on both series of errors. The test indicated that the error when using AR guidance was significantly lower ($p < 0.05$) than the error without guidance. This result implies that our system may provide users with increased targeting accuracy compared to non-guided tasks

Table 1. Targeting Error measured as the Euclidean distance between targeted corner location and actual corner location

Type	No AR Guidance	AR Guided
Mean Error[mm]	13.04	9.88
Standard Deviation[mm]	6.15	5.34
P Value	0.0126	

5. Discussion

We have presented an application of AR for image guidance in emergency neurosurgical procedures. We focused on requirements of portability, ease of use, and cost efficiency to deliver an implementation that is suitable for use in intensive care unit interventions, particularly for placement of an EVD for treatment of hydrocephalus. Evaluations of the user interface will follow in future studies. An initial pilot studied examined the accuracy of the system, as well as offered insight into accuracy compared to non-guided tasks. Initial results look promising, but more evaluation must take place to further characterize the accuracy of the system, particularly with a focus on clinical relevance. Future work will involve assessing user driven segmentation, the alignment of anatomical features internal to the head, and targeting and navigational performance for neurosurgical tasks augmented with the system. Additionally, future work will involve incorporating algorithms to account for the possibility of brain shift, offsetting the position of key anatomy at the time of surgery as well as examining variation in position of the patient-mounted tracker.

6. Conclusions

Effectively inserting an external ventricular shunt is a surgical task that relies heavily on the spatial relationships of neuroanatomical features and the surgeon's ability to recognize such relationships. Preoperative planning is essential to proper navigation, but operating surgeons must still rely on their spatial reasoning skills to perform the task blindly, increasing cognitive load. We have developed an AR application for mobile deployment in intensive care units for image guided shunt placement and performed a pilot assessment of the system's accuracy. Our results indicate that the accuracy of the system is in the range of a few millimetres, but such data is largely inconsequential in the absence of clinically defined thresholds and performance standards. As such, future work will determine the feasibility of the application for use in the clinic, as well as provide performance feedback to fine-tune the implementation and potentially validate its use compared to blind navigation.

ACKNOWLEDGEMENTS

We would like to acknowledge our sources of funding: GRAND NCE, NSERC, and the CAMI CREATE program.

We also acknowledge Kevin Barker of Robarts Research Institute for help constructing the tracking glasses.

REFERENCES

[1] Kusske, J.A., Turner, P.T., Ojemann, G.A., et al., 1973, Ventriculostomy for the treatment of acute hydrocephalus following subarachnoid hemorrhage., Journal of Neurosurgery 38, 591-5.

[2] Mayer, S.A., Rincon, F., 2005, Treatment of intracerebral haemorrhage., The Lancet Neurology 4, 662-72.

[3] Schodel, P., Proescholdt, M., Ullrich, O., Brawanski, A.,

Schebesch, K., 2012, An outcome analysis of two different procedures of burr-hole trephine and external ventricular drainage in acute hydrocephalus., Journal of Clinical Neuroscience 19, 267-270.

[4] Ferdinande, P., 1999, Recommendations for intra-hospital transport of the severely head injured., Journal of Intensive Care Medicine 25, 1441-3.

[5] Voigt, L.P., Pastores, S.M., Raoof, N.D., et al., 2009, Review of a large clinical series: intrahospital transport of clinically ill patients: outcomes, timing, and patterns., Journal of Intensive Care Medicine 24, 108-15.

[6] Saladino, A., White, J.B., Wijdicks, E.F., Lanzino, G., 2009, Malplacement of ventricular catheters by neurosurgeons: a single institution experience., Neurocritical Care 10, 248-52.

[7] Huyette, D.R., Turnbow, B.J., Kaufman, C., Vaslow, D.F., Whiting, B.B., Oh, M.Y., 2008, Accuracy of the freehand pass technique for ventriculostomy catheter placement: retrospective assessment using computer tomography scans., Journal of Neurosurgery 108, 88-91.

[8] Kakarla, U.K., Kim, L.J., Chang, S.W., Theodore, N., Spetzler, R.F., 2008, Safety and accuracy of bedside external ventricular drain placement. Journal of Neurosurgery 63, 164-169.

[9] Hseih, C.T., Chen, G.J., Ma, H.I., et al., 2011, The misplacement of external ventricular drain by freehand method in emergent neurosurgery., Acta Neurological Belgica 111(1), 22-8.

[10] I.E. Sutherland, “A head-mounted three dimensional display,” In Proc. Of Fall Joint Computer Conference 1968, part I, pp. 757-764.

[11] B. Michael, H. Fuchs, and R. Ohbuchi, "Merging virtual objects with the real world: Seeing ultrasound imagery within the patient," In ACM SIGGRAPH Computer Graphics, 1992, vol. 26, no. 2, pp. 203-210.

[12] R.R. Shamir, M. Horn, T. Blum, J.H . Mehrkens, Y. Shoshan, L. Joskowicz, and N. Navab, “Trajectory planning with augmented reality for improved risk assessment in image-guided keyhole neurosurgery,” 2011 IEEE International Symposium on Biomedical Imaging: From Nano to Macro, vol., no., pp.1873-1876.

[13] R. Shamir, L. Joskowicz and Y. Shoshan, “An augmented reality guidance probe and method for image-guided surgical navigation,” 5th International Symposium on Robotics and Automation, San Miguel Regla Hidalgo, Mexico, August 25-28, 2006.

[14] Kockro, R. A., Tsai, Y. T., Ng, I., Hwang, P., Zhu, C., Agusanto, K. and Serra, L., 2009, Dex-ray: augmented reality neurosurgical navigation with a handheld video probe., Neurosurgery, 65(4), 795-808.

[15] Mischkowski, R. A., Zinser, M. J., Kübler, A. C., Krug, B., Seifert, U., and Zöller, J. E., 2006, Application of an augmented reality tool for maxillary positioning in orthognathic surgery–a feasibility study., Journal of Cranio-Maxillofacial Surgery, 34(8), 478-483.

[16] J. Fischer, M. Eichler, D. Bartz, and W. Straßer, “Model-based hybrid tracking for medical augmented reality,” In Proceedings of the 12th Eurographics conference on Virtual Environments, May 2006, (pp. 71-80).

[17] Williams, L.J., 1985, Tunnel vision induced by a foveal load manipulation., The J. of the Human Factors. vol. 27(2), pp. 221-227.

[18] M. Lerotic, A. J. Chung, G. Mylonas, and G.Z. Yang, “pq-space based non-photorealistic rendering for augmented reality,” in Proc. Med. Image Comput. Comput. Assist. Interv., 2007, 10(Pt 2), 102-109.

[19] Vuforia SDK. (2013) Vuforia Developer Portal.[Online]. Available: https://developer.vuforia.com/

[20] Muramatsu, A. et. al., 2008, Reproducibility of maxillofacial anatomic landmarks on 3-dimensional computed tomographic images determined with 95% confidence ellipse method., The Angle orthodontist, 78(3): 396-402.

[21] W. Chen, R. Smith, S.-Y. Ji, and K. Najarian, “Automated segmentation of lateral ventricles in brain CT images,” Bioinformatics and Biomeidcine Workshops. BIBMW 2008. IEEE International Conference on, pp. 48–55.

[22] Chen, W., Smith, R., Ji, S.Y., Ward, K., and Najarian, K., 2009, Automated ventricular systems segmentation in brain CT images by combining low-level segmentation and high-level template matching., BMC medical informatics and decision making, vol. 9, no. Suppl 1, p. S4.

[23] Liu, J., Huang, S., Ihar, V., Ambrosius, W., Lee, L.C., and Nowinski, W.L., 2010, Automatic model-guided segmentation of the human brain ventricular system from CT images., Academic radiology, vol. 17, no. 6, pp. 718–726.

[24] Yushkevich, P.A., et al., 2006, User-guided 3D active contour segmentation of anatomical structures: significantly improved efficiency and reliability., Neuroimage 31.3: 1116-1128.

[25] S. Pieper, M. Halle, and R. Kikinis, “3D Slicer,” Biomedical Imaging: Nano to Macro, 2004. IEEE International Symposium on, pp. 632–635.

[26] Weglinski, T., and Fabijanska, A., 2012, Survey of Modern Image Segmentation Algorithms on CT Scans of Hydrocephalic Brains., Image Processing & Communications, vol. 17, no. 4, pp. 223–230.

[27] Osher, S., Sethian, J.A., 1988, Fronts propagating with curvature dependent speed: Algorithms based on Hamilton-Jacobi Formulations., Journal of Computational Physics, Vol. 79, pp. 12-49.

[28] Grady, L., 2006, Random walks for image segmentation., IEEE Transactions on Pattern Analysis and Machine Intelligence, Vol. 28, No. 11, pp. 1768-1783.

[29] Y. Boykov, M.P. Jolly, “Interactive graph cuts for optimal boundary & region segmentation of objects in N-D Images,” In Proceedings of International Conference on Computer Vision 2011, Vol. 1, pp. 105- 112.

[30] W.E. Lorensen and H.E. Cline, “Marching cubes: A high resolution 3D surface construction algorithm,” In ACM SIGGRAPH Computer Graphics, 1987, vol. 21, no. 4, pp. 163–169.