Image based Data Preparation for Neuronavigation

Abhishek Kaushik, Gaurav Bhutani, Venkata P P K, T A Dwarakanath, Aliasgar Moiyadi

Abstract

In neuronavigation (also known as image guided surgery), the re-constructed CT/MRI image of the patient super-imposed with the moving surgical tool is available on the computer screen in real time to the surgeon. This paper presents the methodology for CT/MRI image based data preparation used for image guided neurosurgery. Patient preparation procedures for neuro-registration based on the surgeon's qualitative assessment are presented. The imaging data acquired from the scan is in Digital Imaging and Communications in Medicine (DICOM) format. The paper discusses layers of information of DICOM and provides an insight into its information architecture. The methodology for DICOM data preparation for neuronavigation is presented. The different Unique Identifiers (UID's) for DICOM are studied and all slices of various views are identified and placed in their appropriate location. Given the DICOM data of a patient, a module is developed to display the three orthographic views, an oblique view of choice and a 3D model of the patient's brain. An algorithm and the corresponding GUI for neuro-registration are prepared, which helps to determine the coordinates of the tumor point with respect to the surgical tool. For registration, the fiducials that appear in the image are marked in the DICOM data and the corresponding fiducials in the physical space are marked using a Surgical Coordinate Measuring Mechanism (SCMM). The implementation of the SCMM based neuro-registration and neuronavigation are demonstrated. The above methodology is demonstrated on various acrylic phantoms and a human skull to validate the data preparation for neuronavigation. The test procedures are found to be in accordance with the neurosurgical standards.

Keywords: Neuro-registration, Neuronavigation, Neurosurgery, DICOM, Medical imaging, Image guided surgery.

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Abhishek Kaushik   (Corresponding author)
Division of Remote Handling & Robotics, Homi Bhabha National Institute, Mumbai, India,
E-mail: abhishekk@barc.gov.in.

Gaurav Bhutani
Division of Remote Handling & Robotics, Bhabha Atomic Research Centre, Mumbai, India,
E-mail: bhutani@barc.gov.in

Venkata P. P. K.
Computer Division, Bhabha Atomic Research Centre, Mumbai, India,
E-mail: panikv@ barc.gov.in.

T. A. Dwarakanath
Division of Remote Handling & Robotics, Bhabha Atomic Research Centre, Mumbai, India,
E-mail: tad@ barc.gov.in.

Aliasgar Moiyadi
Advanced Centre for Treatment Research & Education in Cancer, Navi Mumbai, India,
E-mail: aliasgar.moiyadi@gmail.com

1   Introduction

Neuronavigation involves various technologies to guide the neurosurgeon to locate and operate on the problem area within the confines of the brain. The tip of the surgical tool is projected as crosshairs in the different projections of the re-constructed CT/MRI image data. During the surgery, the surgeon can view in real time, the position of the surgical tool along with the re-constructed CT/MRI image of the patient on the computer workstation. The prerequisite of the neuronavigation is the determination of the relationship of the tumor with the surgical tool, which is obtained in the neuro-registration process. The surgical tool position has to be tracked with respect to the patient's image throughout the surgery. Neuronavigation involves integration of various technologies like imaging modalities, medical image processing, neuro-registration and computer graphics. Some of them are discussed below.

1.1. Imaging modalities

The medical imaging modalities include Computed Tomography (CT), Magnetic Resonance Imaging (MRI), ultrasound imaging, Positron Emission Tomography (PET) and Single Photon Emission Computed Tomography (SPECT). These imaging modalities use tomography techniques for image generation. MRI is a scanning technique used to capture volumetric information of parts of human body in the form of stack of images. MRI uses the radio-frequency waves from the nuclei of hydrogen atoms for image generation. It is based on electromagnetic effects of the nucleus [1]. CT scan is a medical imaging procedure that utilizes computer-processed X-rays to produce tomographic images or 'slices' of specific areas of the body. For Imaging, a volume is acquired slice by slice, and each slice is reconstructed from several measures in different angulations [1]. It can be noted that MRI has better tissue contrast than CT images; because in CT, tissues are identified by their attenuation; whereas in MRI, tissues are identified based on three parameters namely T1 weighted, T2 weighted and proton density weighted image. In this paper, all the images are either CT or MRI based. The other modalities are not discussed in the paper.

1.2. Medical Image Processing

The medical images generated by the medical imaging modalities are in DICOM format. DICOM is a set of standards formulated to maintain the standardization among various stack of images, data types and communication between various modalities, workstations and other devices. DICOM supports up to 65,536 (16 bits) shades of gray for monochrome image display. It records image-related parameters such as patient 3D position, sizes and orientations, slice thickness, radiation doses and exposures, image processing filters, modality used, information related to patient, doctor and hospital. The information makes the DICOM images unique for a particular patient throughout the world. DICOM files and messages use more than 2000 standardized attributes. All these attributes can be found in the standard DICOM data dictionary [2]. These images need to be processed for obtaining useful information related to anatomy of brain and tumor. The re-constructed images are interfaced with various neuronavigation devices and can be used to guide the

surgical tool during surgical procedures. Medical image processing includes various techniques like removal of noise, brightness and contrast manipulation and segmentation of various parts of image. Sometimes, image appears to be very dark or very bright due to which feature of interest may not be visible. In such cases, there is a provision to change the Window Width (WW) and Window Level (WL). Window width (WW) is the range of Hounsfield unit of set of tissue being studied and window level (WL) is central value of Hounsfield unit (HU). The HU range for bone is 400 to 1000, soft tissue is 40 to 80, water is 0, fat is -60 to -100, lung is -400 to -600 and air is -1000 [3]. It may be noted the term attenuation and HU is only applicable to CT images. The setting of WL/WW are generally based on feature of interest; and for neuro-imaging (brain tissue) recommended WL/WW value is 40/128 [4].

2 Data Preparation and Development of Neuronavigation System

Generally, CT/MRI scan is taken in axial direction of the patient and images are generated in axial, sagittal and coronal directions from volumetric data. DICOM image data always have a DICOM entity called DICOMDIR. This DICOMDIR is read first as it contains all information and images belonging to various studies and series. These images are randomly arranged and need to be segregated. Images are segregated based on DICOM Unique Identifiers (UIDs). A patient can have multiple scans like MRI scan of neck or MRI of brain. All these scans of same patient comes under one patient with different studies and allotted different study instance UIDs (0020, 000D) which is unique for each study. A study can have multiple series based on directions like axial, coronal and sagittal or based on scan with contrast medium or without contrast medium. In DICOM, each series is assigned with series instance UID (0020, 000E) which is unique for each series. Each series may have multiple images and each image have unique SOP instance UID (0008, 0018). An algorithm and a software module is developed to read all the UIDs of each image and placed in their respected locations in series and study. Generally images belonging to a particular series have same orientation; but many times series contains some raw images which are of different orientation and does not contain any useful information. These images are searched based on their different orientation from majority of images having same orientation in a particular series. Those images are irrelevant and are discarded. As the aim is to generate 3D volume, if any series contains less than five images then that whole series is also discarded. Basically three coordinate systems are used in acquisition of medical images namely world coordinate system, patient coordinate system and image coordinate system. World coordinate system is a Cartesian coordinate system in which CT/MRI scanner is placed. Every scanner can have its own coordinate system but there is only one world coordinate system. Anatomical or patient coordinate system is also a Cartesian coordinate system but is based on position of placement of patient on scanner table. It is a 3D space containing three planes namely axial, coronal and sagittal. The direction of the axes is defined fully by the patient's orientation. If Anatomical Orientation Type (0010, 2210) is absent or has a value of BIPED, the X axis increases to the left hand side of the patient. The Y-axis increases towards the posterior side of the patient. The Z axis increases towards the head of the patient [2]. In DICOM image coordinate system, X axis increases to the right, the Y axis to the

bottom and the Z axis backwards. Image coordinate system describes how image is acquired by scanner. Scanner generates regular rectangular array. In addition to the intensity value of each voxel (3D volume element), the origin and spacing of the anatomical coordinates are also stored [5]. Images acquired by medical scanner are in 2D and it is required to map the position and orientation of these 2D images with reference to 3D patient coordinate system. The image plane attributes and pixel spacing attributes are used to map the position and orientation of 2D images to patient coordinate system. These attributes are Image Position (patient) (0020, 0032), Image Orientation (patient) (0020, 0037) and Pixel Spacing (0028, 0030). Image position is three coordinates (in mm) of the centre of first voxel at top left corner of the image. Image orientation is direction cosines of first row and first column with respect to the patient. Pixel spacing is the physical distance in patient between centers of each pixel. Image position (patient) also specifies origin of the image with respect to patient-based coordinate system. To map the position and orientation of 2D images in image plane to patient coordinate system, a procedure given in DICOM standard 3.0 [2] is adopted. This procedure is stated below.

$$P_x = X_x . \Delta i. i + Y_x . \Delta j. j + S_x \tag{1}$$

$$P_y = X_y . \Delta i. i + Y_y . \Delta j. j + S_y \tag{2}$$

$$P_z = X_z . \Delta i. i + Y_z . \Delta j. j + S_z \tag{3}$$

Where P_x, P_y, P_z are coordinates of voxel (i ,j) in image plane in mm. S_x, S_y, S_z are the coordinates of Image position (patient) (0020, 0032). It is location in mm from origin of the patient coordinate system. X_x, X_y, X_z are the values of the row (X) direction cosines of image orientation (patient) (0020, 0037) attribute. Y_x, Y_y, Y_z are the values of the column (Y) direction cosines of image orientation (patient) (0020, 0037) attribute. *i, j* are column and row index to image plane. The first row and column index is zero. *Δi, Δj* are column and row pixel resolution of pixel spacing (0028, 0030) attribute in unit of mm [2]. The stated procedure has been incorporated to develop the software module for neuronavigation.

Surgical Coordinate Measuring Mechanism (SCMM): A high precision, light weight, portable SCMM is developed in author's laboratory for neuro-registration and neuronavigation. The SCMM is made of high strength aluminium alloy to reduce the weight of the mechanism. It is a passive four degree of freedom serial mechanism with encoders mounted at each joint and with a base fixture. Neuro-registration experiments are carried out using SCMM.
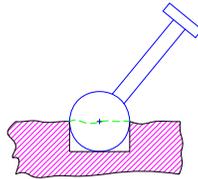
Figure 1: Point-Circumference Contact Nesting

The end link of the serial mechanism is equipped with a probe to suit point-circumference contact nesting measurements. The neuro-registration measurement can be conducted by resting the end stylus of the probe on fiducial points. Highly accurate correspondence is not possible because the point definition is non-existent, and a small regional approximation is done. As shown in Fig. (1), point circumference contact nesting method is used to closely register the tip of SCMM with the centre point of fiducial. The tip of SCMM is ball shaped so that it can fit in the opening of fiducial marker [6]. The complete procedure and detail of registration using SCMM can be found in one of the author's previous paper [6]. At least three non-collinear fiducial points are measured to establish the relation of the fiducial frame with the surgical tool. Fig. (2) shows the prototype of the SCMM.
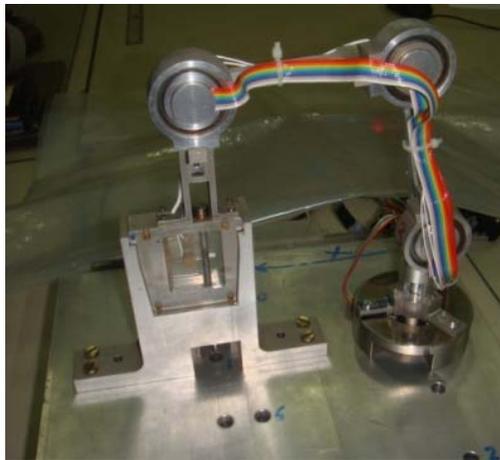
Figure 2: Surgical Coordinate Measuring Mechanism (SCMM)

3   Patient Preparation and Neuro-registration

Neuro-registration is a process of determining the relationship of anatomical frame with respect to a surgical tool frame. The task lies in identifying the point in the image and in real space accessing it for measurement. To map the CT/MRI image of the body part with the corresponding anatomical portion of the real body, specific points on the image are registered with the corresponding real life anatomical points. Patient must be prepared before imaging for neuro-registration. A set of four fiducial markers are affixed on scalp of the patient. A fiducial marker is of the shape of a button (cylinder with a central hole). The main purpose of affixing fiducial marker is that it is visible in CT/MRI images. These fiducial markers are made up of radio opaque material and are used as registration point. The centre of the base circle of the cylindrical hole is taken as the reference point of the fiducial. Mathematical requirements should be taken care such that, no three fiducials should be collinear or near collinear to avoid singularity or ill conditioning. In case four fiducials are used for neuro-registration, care should be taken that all of the four should not lie in a plane. To start neuro-registration, DICOM directory (DICOMDIR) is imported and read so that the axial, coronal and sagittal views are re-constructed and displayed in a window of GUI as shown in Fig. (3). Now for neuro-registration, four predefined

central points at the base of the fiducials are marked in different views of GUI. These points are marked by click of the mouse and once they are selected they are highlighted by red color dots in the GUI. After selecting points in the images, corresponding points are measured by using SCMM in its reference frame. End tip of SCMM is pressed against corresponding points of the phantom to register the physical points with the points in the images. To ease the selection of corresponding points between image and the physical phantom, a 3D model is generated using image data. However, the precision of selection has to be fine tuned in the 2D views. By using 3D model, it is possible to register very complex shapes. Two acrylic blocks of different sizes and a human skull are affixed with fiducial markers. All are successfully registered using the 3D model and the SCMM.
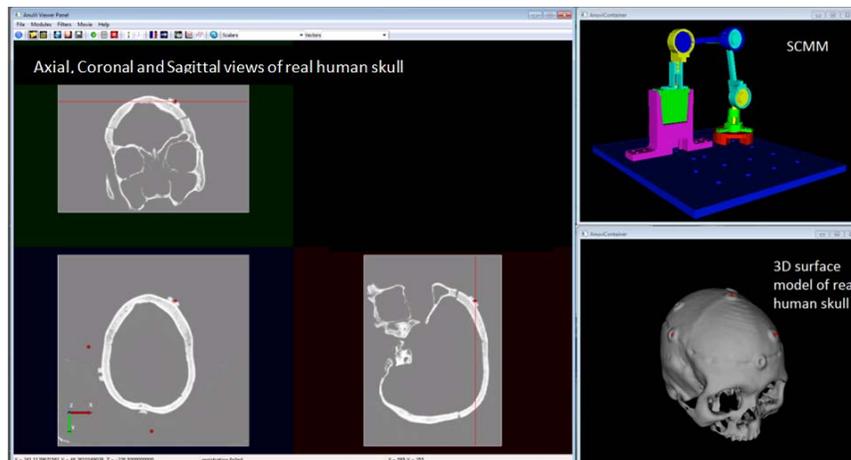
Figure 3: GUI shows axial, coronal and sagittal views along with 3D surface model of human skull and 3D model of SCMM

GUI shows axial, coronal and sagittal views along with 3D model of the human skull and 3D model of SCMM (see Fig. (3)). The red dot indicates the point selected in 3D model of the skull and the corresponding sections containing the point are generated and the point is shown in all the three views. Fig. (4) shows GUI during registration process, a window showing the DICOM coordinates and corresponding SCMM coordinates of the selected points is displayed. Fig. (5) is a zoomed view of table shown in Fig. (4). It may be noted in the GUI that the slice location of one view is indicated by red line in other two views.

Figure 4: GUI during registration

Figure 5: Zoomed view of table shown in Fig. (4)

4   Neuronavigation

A GUI has been developed using wxwidgets, VTK and PyDICOM in python language. The Visualization Toolkit (VTK) is an open-source library for 3D graphics, visualization and image processing and PyDICOM is a python library to read, write and modify DICOM files [7, 8, 9]. For a selected series, the GUI shows various slices at their respected locations. The 3D surface model is generated using marching cube algorithms [10]. Marching cube algorithm is a high resolution 3D surface generation method which extracts iso-surface from scalar volumetric data set. The surface that satisfies F(p) = a, where 'a' is a constant, F(p) is a scalar field with F is a scalar function, is called the iso-surface defined by a. The value of 'a' is called the iso-value [10]. As the dynamic range of the DICOM data is normalized, iso-value can be any scalar value between 0.0 and 1.0. Isovalue of 0.1 is used to extract the skull surface using marching cube algorithm. Along with axial, coronal and sagittal views, an oblique view is also generated. This oblique view is a real time image of the brain normal to the axis of the moving tool. During neuronavigation, the GUI displays axial, coronal, sagittal and oblique views generated at the tip of the tool of SCMM in real time. As seen in Fig. (6), the top right window shows generated 3D model of the skull along with actual position of SCMM during neuronavigation. After neuro-registration, the neuronavigation framework is tested for its accuracy. Table 1 shows DICOM and SCMM coordinates of two anatomical points in DICOM

and SCMM frame of reference and their registration errors (highlighted). The neuro-registration errors are less than 1 mm. The experiments are performed with CT scan data of two acrylic blocks and actual human skull. The implementation of the SCMM based neuronavigation is illustrated in the Fig (7). It shows the SCMM and its simulated model when the user is traversing the surface of the skull. The GUI has a pan, tilt and a zoom feature to visualize the 3D model of the SCMM and 3D surface model of human skull to aid the neurosurgeon during neuro-registration and neuronavigation. Neuronavigation procedure is found to be satisfactory in all the cases. All measurements in various tables are in mm.
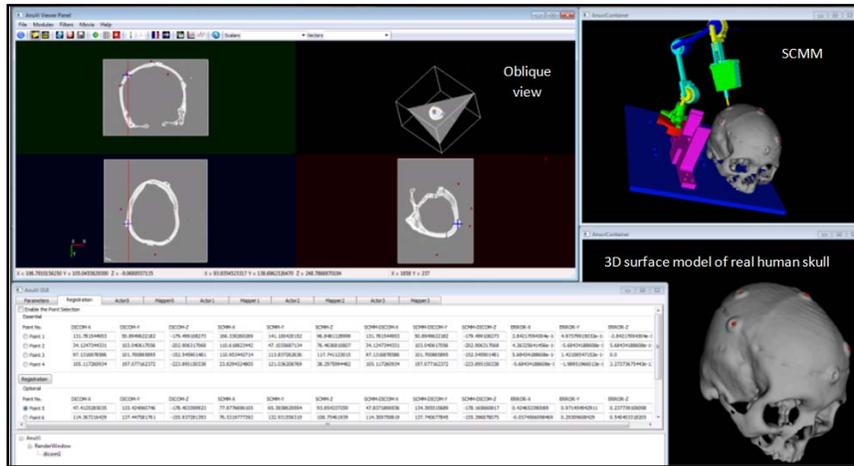
Figure 6: GUI shows all run-time views and relationship of SCMM with respect to 3D human skull model after neuro-registration.

Table 1: Zoomed view of table shown in Fig. (6) Showing DICOM points, SCMM points and neuro-registration error.

points	DICOM X	DICOM Y	DICOM Z	SCMM X	SCMM Y	SCMM Z	SCMM DICOM X	SCMM DICOM Y	SCMM DICOM Z	Error X	Error Y	Error Z
5	47.412	133.424	-178.403	77.877	65.393	93.854	47.837	134.395	-178.165	0.424	0.971	0.2377
6	114.367	137.447	-155.	76.532	132.931	108.754	114.309	137.740	-155.	0.057	0.293	0.540
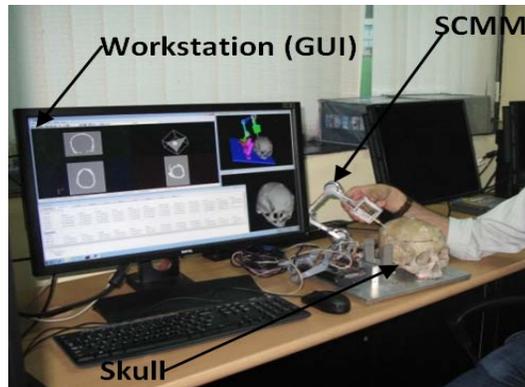
Figure 7: Neuronavigation procedure demonstrated for SCMM

5   Conclusions

Neuronavigation system has been developed using SCMM and software interface conforming the DICOM standard. Step by step procedure of neuro-registration and neuronavigation are discussed in detail. The ease of neuro-registration is enhanced by generating a 3D model form the DICOM images. The experiments have been established to validate the SCMM based successful neuro-registration and neuronavigation procedure. The actual configuration of the SCMM was visualized on the computer screen along with the tool movement relative to the 3D model of the human skull when the user manually navigates the end tool fixed to the SCMM. By use of point to point registration through portable SCMM, the problem of camera mounts and the line of sight constraints is eliminated. Procedure to point to the infinitesimal region repetitively is developed to minimize the error in measurement.

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