Neuro-Registration and Navigation Unit for Surgical Manipulation

Gaurav Bhutani, T A Dwarakanath, K D Lagoo
Division of Remote Handling and Robotics,
Bhabha Atomic Research Centre,
Mumbai, India
Email: bhutani@barc.gov.in, tad@barc.gov.in, klagoo@barc.gov.in

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

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

***Abstract* — The paper deals with the synthesis, development and implementation of a neuro-surgical registration unit for neuro-surgical procedures. The neuro-surgical registration unit consists of a portable Surgical Co-ordinate Measuring Mechanism (SCMM), a 3 DOF spatial parallel robot and the related imaging and graphic components. A portable SCMM is developed and demonstrated for registration of the anatomical spatial points and for carrying out neuro-navigation procedures. The fiducial based registration and surface based registration procedures using SCMM are described. The accuracy of the SCMM unit is analyzed. Further the advantage of the SCMM over current practices in navigation is discussed. Also, a 3 DOF spatial parallel robot developed in the author's laboratory is used to perform a robot based neuro-navigation. Imaging and graphic modeling components for SCMM based neuro-navigation and robot based neuro-navigation are developed.**

***Keywords* — Neuro-navigation; localization; coordinate measuring mechanism; robotic neurosurgery; neuro-registration; image-guided surgery.**

I. INTRODUCTION

In image guided surgery, the CT/MRI image data of the patient along with the position of the surgical tool will be available on the computer screen to the surgeon. Neuro-navigation basically means: during the surgery, the surgeon can view in real time the position of the surgical tool along with CT/MRI image of the patient on the computer workstation. The pre-requisite of the neuro-navigation is initial registration of patient with the imaging data. Extensive research is being carried out on the subject of stereotaxy procedures in the field of neuro-navigation. The interest in active registration and real time navigation in neurosurgery is gaining pace. As a result highly intricate maneuvering is being done and smaller and smaller size tumors are being removed. There has been considerable progress in this field. The measuring probes and pick up tools can be made to access otherwise inaccessible regions and effect minimally invasive surgery. The tool or probe guiding mechanisms are consistent throughout the surgery and follow the set procedures with utmost precision. All these greatly aid the surgeon, when they attempt to perform highly intricate minimally invasive surgical procedures. The first attempt success rates as well as the enhanced quality of surgery are the benefits.

CT, MRI and many other imaging techniques can be used to identify the tumor in relationship to the external frame [1, 2]. The speed of improvements in imaging equipments, tools and techniques have resulted in high quality diagnosis and measurement. The reconstruction of any sectional view of the image has helped to assess the location, extent and form of the problem very closely. The procedural steps for any of the imaging techniques are similar. Body attached physical frame and non body attached physical frame for localization of tumor is in practice [3, 4, 5]. The physical frame based stereotactic surgery became very popular and has been accepted for long over five decades now [6, 7, 8]. For the last one decade, due to technological progress, a transition towards eliminating physical frame and practice of frameless stereotaxy is gaining momentum [9, 10]. The reasons to find an alternative course are because of the disadvantages in managing the physical frame. The patient has to wear the bulky frame for a long duration, from the time of the imaging till the completion of the surgery. Sizing of the frame to fit different head dimensions occurring across age groups and gender is difficult. The presence of the frame around the head causes hindrance to manipulate the surgical tools. Any displacement or removal of the frame amounts to loosing the reference; thereafter any surgical follow up procedure is not possible because of the loss of the reference. More and more frameless localization procedures are being developed and are steadily taking over the localization and stereotactic procedures [11, 12, 13]. Recently optical or camera based tracking is well accepted for the use in frameless based neuro-navigation systems. Generally the frame based stereotaxy is having much better accuracy than camera based frameless based stereotaxy procedures. The aim of the research presented in the paper is to develop a frameless based neuro-navigation procedure having the accuracy comparable to frame based accuracy.

Section 2 of the paper presents the design and development of a portable Surgical Co-ordinate Measuring Mechanism (SCMM) for frameless localization procedures. The compact prototype design, eliminating camera mounts and the line of sight constraints is the highlight of the portable SCMM. Procedure to point to the infinitesimal region repetitively is developed to minimize the error in measurement. One instant registration of spatial point to avoid uncertainty range of points is considered carefully. The control electronics and software for registering the spatial point is implemented. The localization of the region representing the tumor is done by conducting the experiments on a phantom. The localization algorithm is discussed. Experiments and the results of successful mapping from the image frame to the robot frame of reference are discussed in detail. In section 3, surface registration experiments are carried out using SCMM. The surface registration experiments are cross verified and evaluated using a high precision 3 DOF spatial parallel mechanism developed at author's laboratory. Section 4 presents the experiments on passive mechanism based image guided surgery and autonomous robot based image guided surgery on a human phantom. The results obtained and the relative accuracies are presented.

II. NEURO-REGISTRATION AND SCMM

A. *Preparation for Neuro-registration*

Neuro-registration is a process of recording co-ordinates of an anatomical point with respect to a surgical frame of reference. The task lies in representing a point in real space and accessing for measurement. On machine elements, the geometry of the elements will have well defined geometrical shapes, geometrical references can be employed or measuring probe can be guided to access a point uniquely (with very high tolerance). Such referencing or constraints to guide a measuring probe to a specific anatomical point is often not available. 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. Highly accurate correspondence is not possible because the point definition is non-existent, and a small regional approximation is done. Also visual errors in accessing and contacting a point with a probe will also add to the error. The typical error is around five millimeter. The consequence of these errors is of increased uncertainty and results in extended boundary of surgical portion. In guided biopsy pick up in neurosurgery, such registration errors causes offset in position and orientation of the needle mounting reference surface. The translation and orientation shift of the plane would greatly offset the needle from the target due to multiplying effect of the traversed length of the needle with the orientation error. To minimize measurement error in registration, a definitive definition for the point has to be obtained. Certain simple methods are developed based on the practices in coordinate measuring methods in machine elements. Fig. 1 suggests some of the methods to create near exact point definition. The center mark in each figure is constrained and can be identified with very small deviation (of the order of 15 to 20 μm). The magenta colored fixture in fig. 1 is a specially designed fiducial to match the measuring probe and the constrained center mark represents a point.

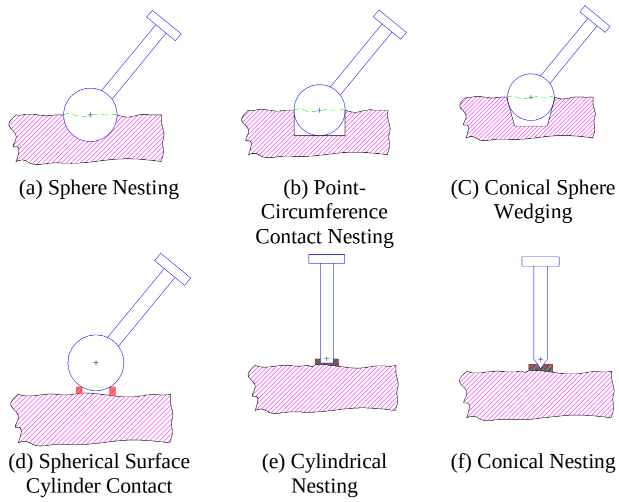

Fig. 1. (Color online) Point measuring configuration of the end probe

Three or more fiducials are affixed on the scalp prior to CT/MRI scan to aid the coordinate measurement and to establish a high precision reference plane. To establish a reference plane, termed as fiducial plane, more than three fiducials are affixed on the scalp. The fiducial is a radio opaque marker, which resembles a button in shape, a cylinder with a cylindrical hole. The centre of the base circle of the cylindrical hole is taken as the reference point of the fiducial. The main property of the radio opaque marker is its visibility in CT/MRI image. Mathematical requirements should be taken care of that no three fiducials should be affixed in collinear or near collinear fashion to avoid singularity or ill conditioning. In this analysis we chose to affix four fiducials (points on the scalp) and name it as A, B, C and D as shown in the fig. 2. With these fiducials, the CT/MRI is taken. The CT/MRI scan output is a collection of DICOM images of a section progressing in discrete slices normal to the section. The resolution of the slices depends upon the manufacturer and varies from 0.1 mm to 5 mm.

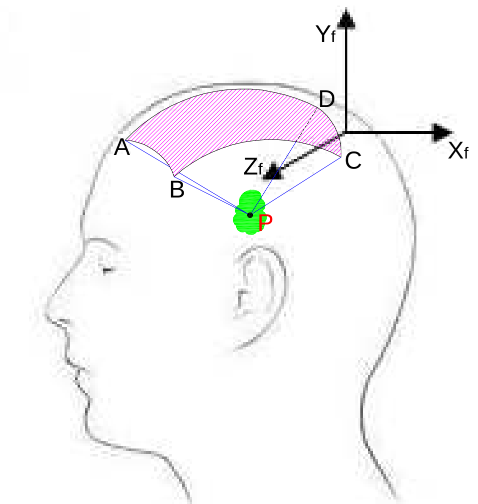

Fig. 2. (Color online) Sketch showing fiducial frame, fiducial points A, B, C and D on the scalp and tumor point P

The fiducials and tumor (if present) would appear in the CT/MRI image. The tumor would appear as a region, progressively increasing or decreasing depending upon the shape of the tumor. The center point of the tumor is marked based on the visual estimate of the tumor shape and size. Fig. 2 explains the typical fiducial point arrangement, the fiducial frame and a problem point at the estimated centre of the tumor region. A DICOM viewer's software is used to view the CT/MRI images. A common reference frame, termed in this paper as fiducial frame F, is attached in all the images of the section in the viewer software. The viewer software also provides a cross-wire cursor to navigate on the image and on click at a point of interest will give co-ordinates of a point with respect to F. A, B, C and D are measured with respect to the fiducial frame of reference.

B. *SCMM (Surgical Co-ordinate Measuring Mechanism)*

Synthesis of the SCMM (fig. 3) is done such that it can be positioned in the desired measurement space and can satisfy manipulability requirements. The basic characteristics of the metrology arrangement for a medical setup apart from the required least count in measurement is that it should be portable and should be easy to use. The SCMM is made of high strength aluminium alloy to reduce the self weight of the mechanism. A passive four degree of freedom serial mechanism with encoders mounted at each joint and with a base fixture is implemented. The end link of the serial mechanism is equipped with a probe to suit point-circumference contact nesting measurements (see fig. 1b). The joint encoders reading are the inputs for a direct kinematic problem to compute co-ordinates of the reference point on the end-probe with respect to the SCMM base frame (this frame is in fixed and known relation with the robot frame). The co-ordinate measurement is obtained on pressing a spherical probe in a nest (bringing the spring loaded electrode in contact with the rigid conducting surface to close the switch).

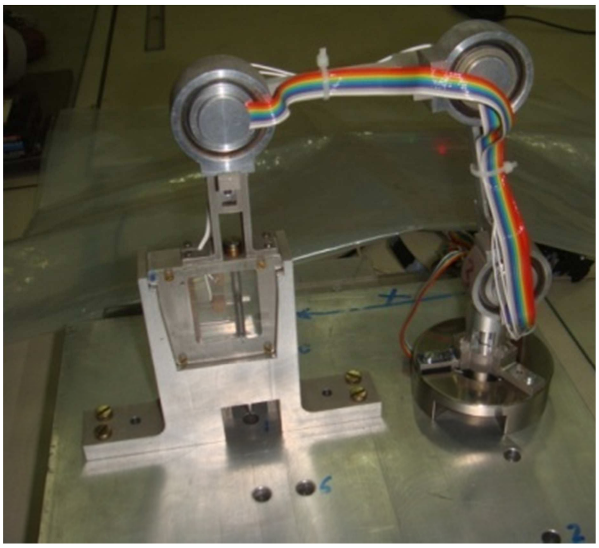

Fig. 3. (Color online) Surgical Portable Coordinate and Path Registering Mechanism

The end-probe mechanism and circuitry is designed to remain in same configuration so as to result in a single instance of a position. At the instant of closing the switch, the encoder values are recorded and the co-ordinates of the end reference point are computed. However, on track mode (switch is in closed condition), the encoder values are polled at high frequency and the co-ordinates of the end point path is computed in high resolution. The prototype of the SCMM system is shown with homing fixture in fig. 3. The SCMM is used to measure the co-ordinates of the fiducial points with respect to the robot frame of reference. The co-ordinate measurements are needed to establish a relationship between the fiducial frame and the robot frame.

C. *Fiducial frame to Robot Frame Transformation*

From image, using DICOM viewer, the co-ordinates of fiducial points with respect to fiducial frame are measured (see fig. 2).

$$^{f}P_A = \{X_A, Y_A, Z_A\}, {}^{f}P_B = \{X_B, Y_B, Z_B\},$$
$$^{f}P_C = \{X_C, Y_C, Z_C\} \text{ and } {}^{f}P_D = \{X_D, Y_D, Z_D\}$$

The co-ordinates of the fiducial points A, B, C and D are measured using SCMM.

$$^{R}P_A = \{X_A, Y_A, Z_A\}, {}^{R}P_B = \{X_B, Y_B, Z_B\},$$
$$^{R}P_C = \{X_C, Y_C, Z_C\} \text{ and } {}^{R}P_D = \{X_D, Y_D, Z_D\}$$

The transformation matrix, $^{R}[T]_f$, which transforms the points that are known in fiducial frame to robot frame is obtained as following.

$$^{R}(P_A, P_B, P_C, P_D)_{4\times4} = {}^{R}[T]_{f(4\times4)}\,{}^{f}(P_A, P_B, P_C, P_D)_{4\times4}$$

Writing the above equation in short form, we have

$$^{R}(P) = {}^{R}[T]_f\,{}^{f}(P) \quad (1)$$

The solution of $^{R}[T]_f$ in (1) for a general case is given in [14] and for completeness given in (2)

$$^{R}[T]_f = {}^{R}(P)\,{}^{f}(P)^T\left[{}^{f}(P)\,{}^{f}(P)^T\right]^{-1} \quad (2)$$

The tumor point is obtained in the robotic frame of reference using the transformation

$$^{R}(P)_p = {}^{R}[T]_f\,{}^{f}(P)_P \quad (3)$$

where, $^{f}(P)_P$ is the position of the tumor point in the fiducial frame of reference. All the fiducial points, tumor point, surgical tool, surgical path of the tool, all are determined in robot frame of reference as explained in fig. 4.

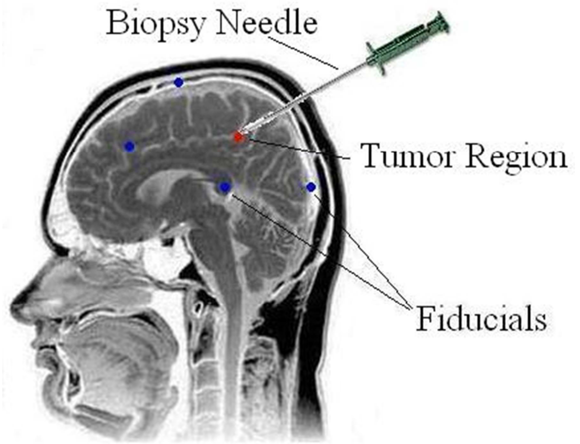

Fig. 4. (Color online) The blue points are fiducials (registered points) and form a reference frame. The tumor is established with respect to the fiducial frame from the CT/MR image data. Latter transformed to robot frame of reference. Rigid body motion of a surgical tool is localized with respect to robot frame.

D. Experimantation for Pair Point Registration using SCMM

Experiments are conducted to evaluate the performance characteristics of the SCMM. A phantom is prepared on which fiducials are pasted and by imaging techniques; the relationship of the tumor with respect to fiducial frame is being established. The phantom is a perspex block on which fiducials are pasted on pre-defined points. The SCMM along with perspex block is shown in fig. 5. CT scan is performed on phantom and the relationship of fiducials among themselves is established. Using the same phantom, the accuracy and repeatability analysis of SCMM is carried out.

Calibration is done, the repeatability of SCMM to measure a point is found to be less than 80 µm. The single point articulation test for SCMM is carried out according to ASME Standard B89.4.22 [15] for Articulated Arm Coordinate Measuring Machines.

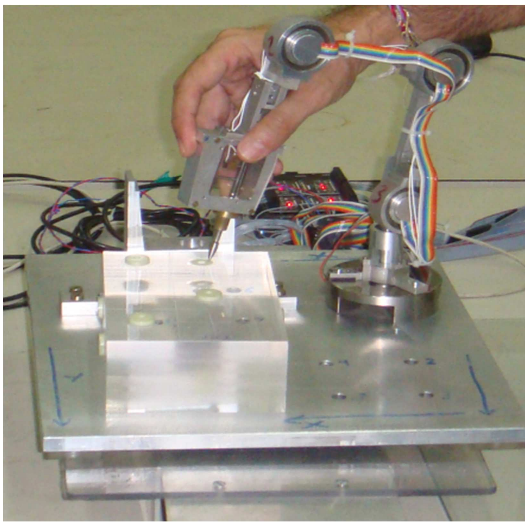

Fig. 5. (Color online) SCMM along with a perspex block

For measuring the accuracy, first set of distances between fiducials already pasted on the perspex bock is measured with SCMM. The second set of the same distances are measured by using a high precision Coordinate Measuring Machine from a metrological department. The two sets of readings are compared to determine the accuracy of the SCMM. The difference in reading is found to be less than 300 µm.

III. SURFACE CO-ORDINATE MEASURING AND REGISTRATION

In pair point based registration there are a relatively small number of point pairs that describe corresponding locations in two coordinate frames (CT/MRI frame and Patient frame). In surface registration there are two large sets of points that describe the same surface, but there are no point pairs [5]. The purpose of surface registration is to match the two sets of data for the same surface. Surface co-ordinate registration and navigation is an application and is shown in the fig. 6. Typically, in some neuro-procedures, certain external anatomical points on the surface have a definite relationship with the inaccessible problem points. Therefore mounting fiducials to create a temporary reference can be avoided. The geometric relationship between the accessible surface features and the inaccessible problem points is built using scanned images. The co-ordinates of the accessible external spatial points are to be registered accurately to create a local reference frame. In this application we demonstrate the accurate measurement and navigation employing the SCMM on a human skull phantom. The surface registration measurement can be conducted by moving the end probe of the last link of SCMM on the surface of the human skull phantom using a track mode. The angular positions of the encoders are polled at high frequency and co-ordinates of the point on the path are computed. The surface co-ordinates are used to establish the relation of SCMM frame with surface of phantom using least square method discussed in section III (C). Fig. 7 shows the surface generated by the SCMM.

The accuracy of the surface generated by the SCMM is verified by comparing with the surface generated by a high precision 3-UPU (Universal – Prismatic - Universal) manipulator developed in the author’s laboratory. The UPU manipulator developed is a 3 DOF pure translational parallel manipulator [16]. Each leg of the manipulator is a kinematic chain which consists of a passive universal joint connected to the base, an active prismatic joint and the universal joint connected to the platform. The precision of the 3-UPU manipulator is in the order of 30 µm. Fig. 8 shows the arrangement of the 3-UPU manipulator measuring the co-ordinates of the points on the surface of the human skull. The skull is placed on the platform of the highly sensitive 6 axis Force Torque (F-T) sensor developed at author’s laboratory [17]. The measuring probe is made to travel till the threshold of force magnitude is less than 0.1 N. The stop command is triggered as soon as the threshold is crossed. The manipulator could successfully stop within very small distances exhibiting fine motion control. The compliance corresponding to 0.1 N is estimated to be 20 µm. The coordinate could be recorded based on direct kinematics at the rested point. The distance between the several specific points on the skull is repeatedly measured and it is found that the repeatability is within 30 µm over a distance of up to 80 mm. Fig. 9 shows the surface generated by the manipulator based measurement. The surface generated by the surgical SCMM was found to be in close agreement with the actual surface as well as the surface generated by 3-UPU manipulator. The maximum deviation is found to be within 500 µm from the surface generated by 3-UPU.

In surface registration, first set of data is generated from the preoperative CT scan data and the second set is generated from the surgical SCMM which is traversed on the patient's scalp. A surface to surface matching algorithm can be used to calculate the transformation which matches and aligns two sets of points generated. This transformation can be used by the neurosurgeon to perform an image guided surgery or also termed as neuro-navigation. The development of the transformation using surface registration is out of the scope of this development.

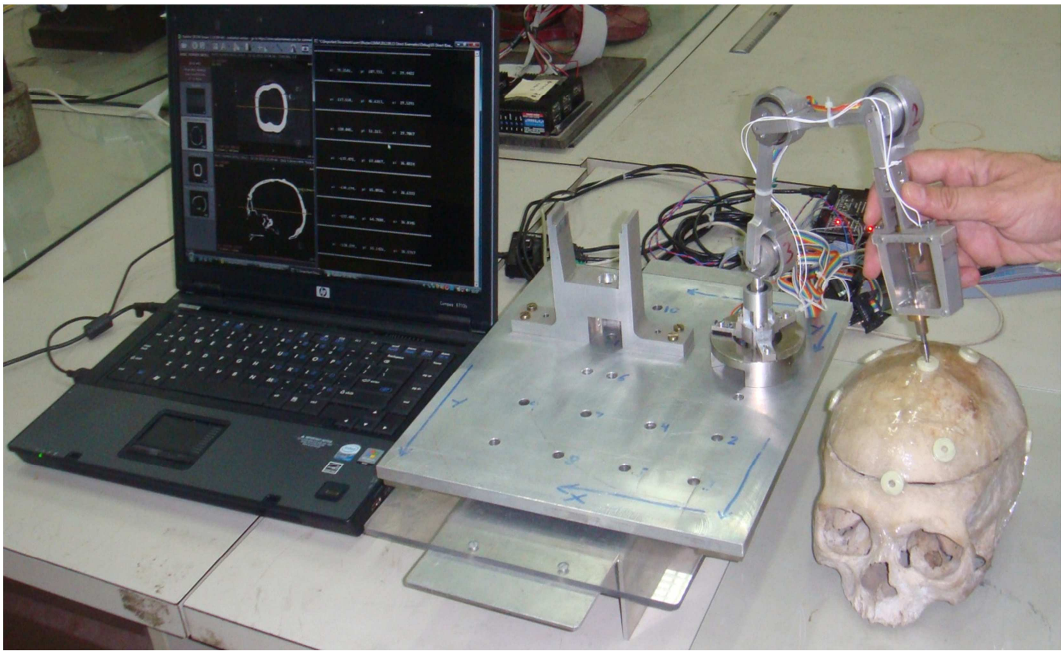

Fig. 6. (Color online) Surface co-ordinate registration of a human skull by SCMM

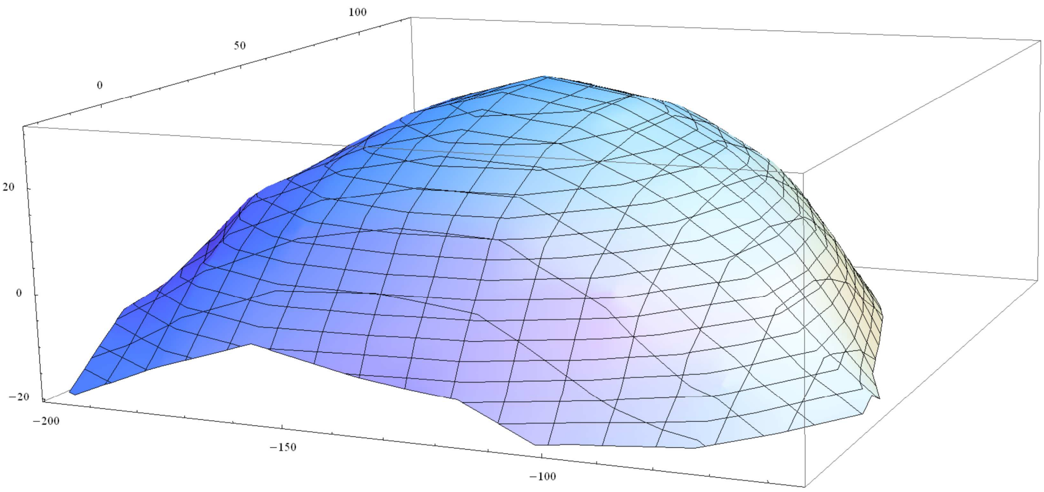

Fig. 7. (Color online) The surface generated by the SCMM

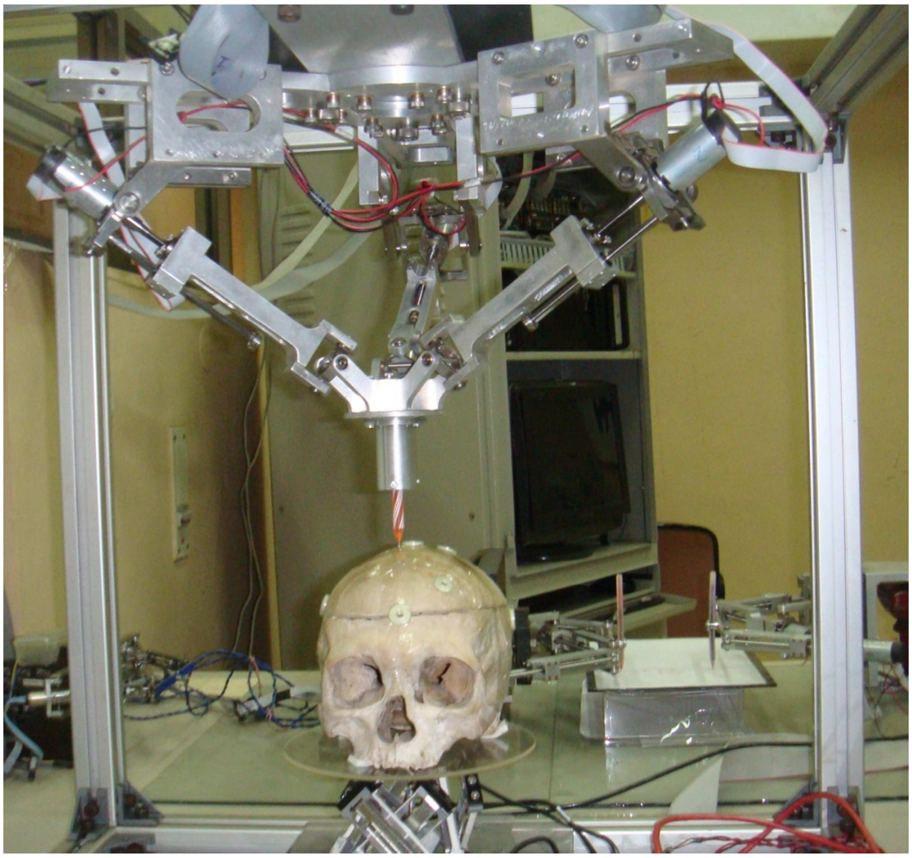

Fig. 8. (Color online) 3-UPU manipulator is being used as a co-ordinate measuring manipulator and tracing the surface for localization purpose

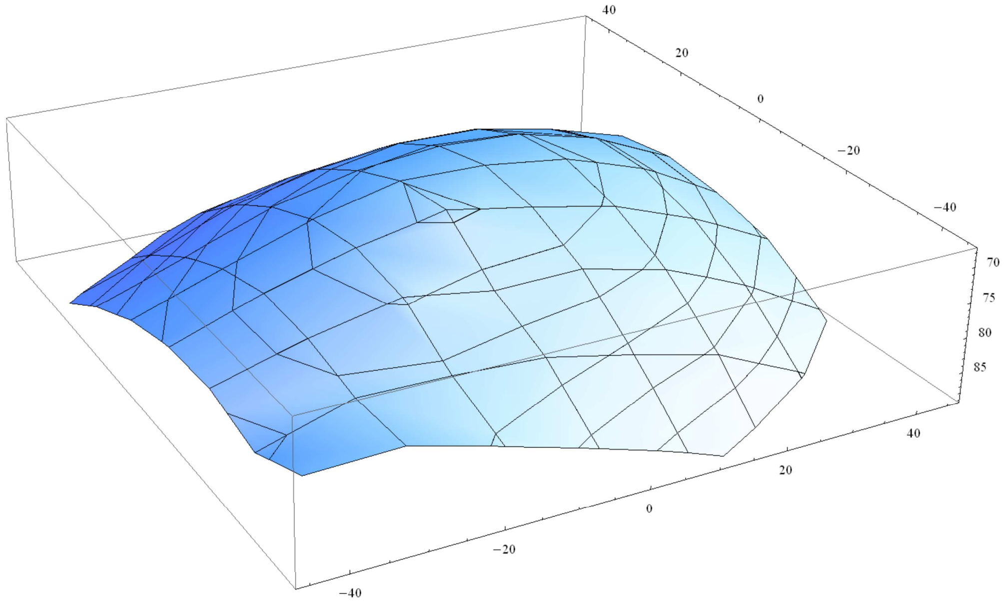

Fig. 9. (Color online) The surface generated by the 3-UPU manipulator

IV. EXPERIMENTATION ON NEURO-NAVIGATION (IMAGE GUIDED SURGERY) AT AUTHOR'S LABORATORY

The major problem, the neurosurgeons face is that they, on seeing cannot distinguish between healthy tissue and affected tissue. It is only in the CT image the region of affected tissue can be seen and can be distinguished from the rest. Therefore the surgeons rely on the image to study the location and extent of the affected region. Large and near surface tumors are removed by localizing with respect to nearby body part and constantly referring to the image. To ensure complete removal of the affected tissue, a negative margin is always kept, thus a layer of healthy tissue along the boundary of the affected region is removed. However medium, small and deep rooted large tumors cannot be removed by this method. There will be high risk of losing the reference and localizing the affected region becomes impractical. Surgeons need continuous reference for localizing the surgical tool. Neuro-navigation means to take continuous reference to conduct the neurosurgical procedure. The neuro-navigation is also termed as image guided surgery. Image guided surgery is as if the surgeon is in an active feedback loop. While performing the surgery, the neurosurgeon can see in real time, the current position of the surgical tool and the mechanism carrying the tool with respect to the image in 3D real time graphics. The surgeon can have a complete view of the surgical tool, its movement, its location along with the reconstructed graphics model of the image. The surgical tool position can be tracked with respect to the patient throughout the surgery. The surgeon takes continuous corrective action to regulate the tool towards the affected region and can visualize this effect on the monitor with a high resolution. The relationship of the tumor and the surgical tool has to be established during registration procedure before performing neuro-navigation. The registration techniques which can be used are point to point fiducial based registration or surface based registration explained in sections II and III respectively.

A. *Demonstration of Neuro-navigation using SCMM*

A point to point fiducial based registration and neuro-navigation is demonstrated in the laboratory. Neuro-navigation experiments are conducted using a human skull phantom to evaluate the performance characteristics of the SCMM. Human skull phantom is prepared for CT by affixing fiducials on the surface of the scalp. CT scan of the phantom is performed and the relationship of the fiducials with respect to fiducial frame is established. The relationship of the tumor (a fixed point on the skull phantom) with respect to the fiducial frame is determined. Using the transformation formulated in section III (C), the co-ordinates of the tumor with respect to SCMM base frame is determined. Subsequent to the registration, the neuro-navigation procedure is carried out.

The neuro-navigation has been implemented in both manual and autonomous setups. The first setup involves using the passive SCMM to navigate the surgical tool. When the user manually navigates the end tool fixed to the SCMM (as in fig. 6), he can visualize on the computer screen, the actual configuration of the SCMM, tool movement relative to the 3D model of the CT image and also the tip of the tool with respect to tumor region. The implementation of SCMM based neuro-navigation is shown in the fig. 10. The fig. 10 comprises of CT image converted into transparent 3D model and SCMM graphic model based on actual size. Simulated input data of joint encoder values are taken for conducting neuro-navigation.

B. *Demonstration of Neuro-navigation using a Parallel Robot*

Autonomous neuro-navigation is conducted using a 3-UPU parallel manipulator. This involves using a parallel robot to navigate the surgical tool autonomously to the tumor point. The robot frame of reference is in a fixed and known relationship with respect to SCMM frame of reference. Hence the relationship of fiducials with respect to the robot frame of reference can be determined. The same CT image as above is used for this purpose. The task space trajectory is decided based on the tumor point and the entry point on the scalp. The autonomous neuro-navigation based experiment is shown in fig. 11.

There can be multiple sources of errors in the neuro-navigation surgery. These are errors due to resolution of imaging data, fiducial registration errors, robot registration error, target registration errors. The accuracy achieved in the neuro-navigation experiments at author's laboratory is less than 1 mm. This accuracy is much better that the camera based frameless stereotaxy procedures which are presently followed. Also this technique removes the line of sight problem which is a big limitation of the current neuro-navigation techniques.

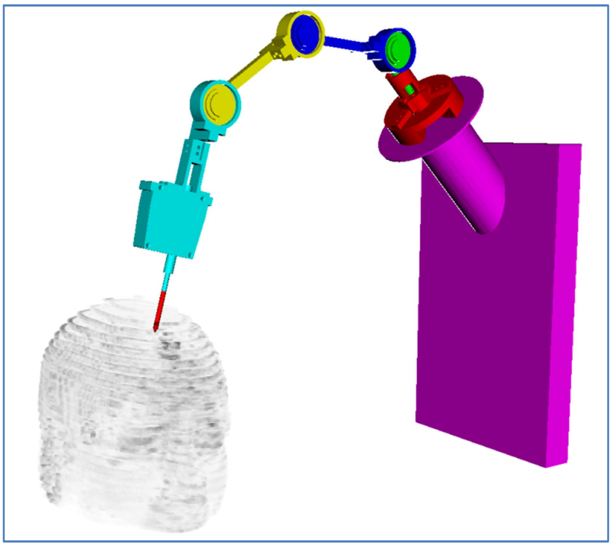

Fig. 10. (Color online) Manual surgeon assisted neuro-navigation

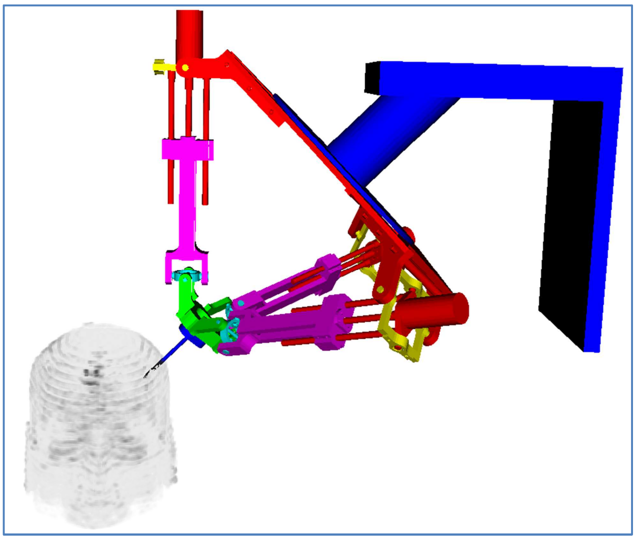

Fig. 11. (Color online) Autonomous neuro-navigation

V. CONCLUSION

Neuro-registration is discussed in detail. Brief account of registration of points on the image and mapping the point to real fiducial points on the scalp is formulated and obtained. A careful analysis of point representation and measurement is presented. Implementation and use of portable SCMM for neurosurgical procedures is demonstrated. The accuracy of the unit in the fiducial and surface based registration is presented. Further the usefulness of the device in navigation is discussed. Both manual, passive mechanism based image guided surgical procedure and autonomous robot based image guided surgical procedure is demonstrated on the skull phantom. The experiments and demonstration to validate the SCMM, successful neuro-registration and navigation have been conducted. The achievable accuracy of the frameless technique used in the paper is much better than the accuracy achieved by camera based frameless stereotaxy. The procedure presented in the paper removes the line of sight problem which is a limitation of the current neuro-navigation procedures.

REFERENCES

[1] http://www.howstuffworks.com/search.php?terms=CT+scan

[2] http://en.wikipedia.org/wiki/X-ray_computed_tomography

[3] Jian Zheng, "An Accurate and Efficient Target Localization method for Stereotactic Neurosurgery of Parkinson's Disease," *PhD Thesis, The State University of New Jersey,* October 2006.

[4] http://en.wikipedia.org/wiki/Stereotactic_surgery

[5] G Eggers, J. Muhling, R Marmulla, "Image-to-patient registration techniques in head surgery," *International Journal of Oral and Maxillofacial Surgeons*, vol. 35, pp. 1081-1095, 2006.

[6] Leksell L, "Stereotactic Apparatus for Intercerebral Surgery," *Act Chir Scand*, vol. 99, pp. 229-223, 1949.

[7] Leksell L, "The stereotaxic method and radiosurgery of the brain," *Act Chir Scand*, vol. 102, pp. 316-319, 1951.

[8] Leksell Stereotactic System, Elekta Instrument AB, Manual

[9] http://www.elekta.com/

[10] http://www.ndigital.com/medical/polarisfamily.php

[11] http://www.brainlab.com/

[12] S. Frey, R Comeau, B Hynes, S Mackey and M Petrides, "Frameless Stereotaxy in the nonhuman primate," *NeuroImage,* vol. 23, pp. 1226-1234, 2004.

[13] N.L. Doward, "Frameless Stereotactic biopsy with the EasyGuide," *Medicamumdi*, vol 42, Issue 1, March 1998.

[14] Lawson, C. L., Hanson, R. J. Solving Least Squares Problems. Englewood Cliffs, NJ: Prentice-Hall. ISBN 0-13-822585-0, 1974.

[15] Methods for Performance Evaluation of Articulated Arm Coordinate Measuring Machines (CMM), ASME B89.4.22 Standard.

[16] Gaurav Bhutani and T. A. Dwarakanath "Practical feasibility of a high-precision 3-UPU parallel mechanism," Robotica, available on CJO2013. doi:10.1017/S0263574713000696, Accepted June 17 2013.

[17] T A Dwarakanath and Gaurav Bhutani, "Beam type hexapod structure based six component force-torque sensor," Mechatronics, Volume 21, Issue 8, pp. 1279 – 1287, 2011.