A ray-traced texture mapping for enhanced virtuality in image-guided neurosurgery.

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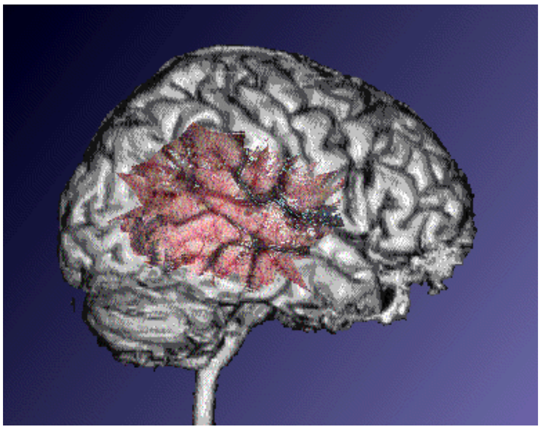
Abstract. 3D imaging systems and algorithms give virtual representations of the real world. New emergent hardware systems create links between virtual information and the real world. They allow the simulation and the remote performance of a real action. For instance, in image-guided surgery, 3D digitizers (localizers) give information from the real world to the virtual one and robotics environment from the virtual world to the real one. Virtual and real information must be also visually confronted to facilitate their understanding. The solution, we propose here, is the superimposition of the real view of the anatomical regions concerned by a surgical act with the 3D digital data sets. Rather than the solutions which display the virtual images in the real world, our method consists in a ray traced texture mapping which provides the display of real images in a computed world.



1. Introduction

The development of digital technologies has allowed the medical community to view inside the whole body without physical injury. 3D algorithms permit now the scanning of the whole acquired volume at any incidence. The surgeon can prepare, on the image itself, the act he is to perform. The 3D digital data sets can be modified and displayed as required, thus permitting a complete simulation of the surgical act[1], so called image guided planning. With multimodal image guided planning, the surgeons have to integrate, in a visual way, a large amount of information. This integration is

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usually performed in a mental way. The next step of the simulation is to use this virtual information for direct action in the real world, so called image guided surgery.

In the neuro-surgery field, the real anatomy of the patient, viewed in the **O**perating **R**oom (OR) context, is more complex to analyze than the three-dimensional digital data sets available for the surgeon. It is due to the operating field (surgical tools, compresses, sheets, ...) and to the restricted opening area (only the anatomical areas involved by the act are visible). Moreover, through the skull resection, differents anatomical parts or objects are visible (vessels, blood, duramater, skull, ...) whereas the digital data sets are often segmented and represent only one modality at time. The capability to superimposed the real view of the anatomical regions concerned by the act with the 3D digital data sets will bring to the surgeon additional information to facilitate the links between real and virtual worlds.

Superimposition between real and virtual images

This superimposition could be done by projecting virtual images on the corresponding real anatomical area of the patient. This solution, called enhanced reality, has been already mentioned by different research labs[2,3,4,5,6] which used virtual reality systems in the OR[7,8]. In such systems, the basic idea is to show the virtual images through an optical system (glasses, mirrors, ...) with a transparency effect which allows to see the patient anatomy behind. The position of the optical system is known in a global coordinate system either at the beginning of the session, if the system is fixed, either at any moment if the system can be moved. The corresponding 3D images are computed relatively to the new position and displayed in the optical system. That way the surgeon can keep his attention on the the patient. He does not have to turn his eyes in order to look at the computer screen. The problems induced by these solutions concern the 3D to 3D registration software and the development of dedicated Virtual Reality hardware to allow the visual mixing.

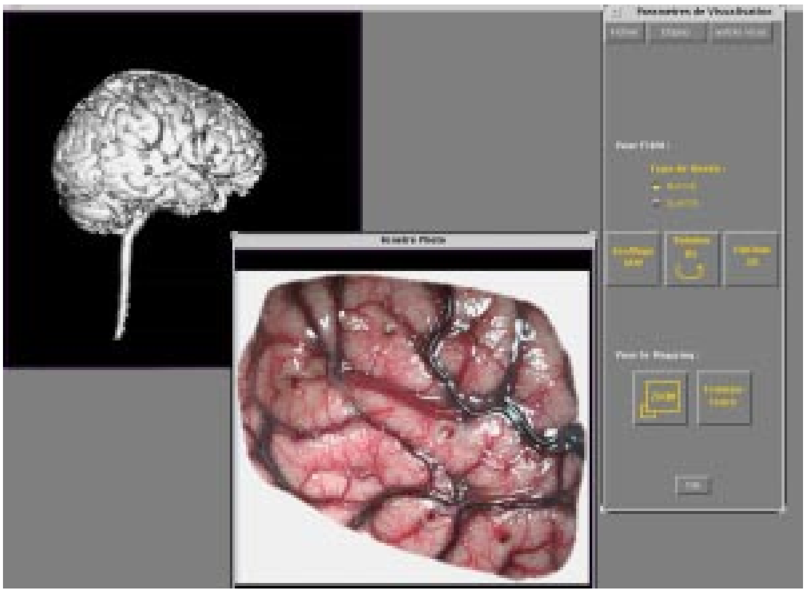
The visual confrontation of real world (corresponding here to real images) and the virtual world (corresponding to the 3D synthetic data sets) can be done by the insertion of the virtual data in the real world. It corresponds to the 2D projection and display of the 3D data sets on a real 2D image or directly on the patient himself. But this confrontation can also be done by the insertion of the real information in the virtual world. This could be done by the projection (mapping) of the real 2D snapshot on the 2D virtual image or directly on the 3D data set.

These two different solutions are usually requiring the knowledge of the 3D information in the real and the virtual worlds. So, optical or stereoscopic systems are used to recover the 3D nature of the real world. The method presented here does not require such systems. This paper concerns the preliminar study to prove the feasibility of a new approach of texture mapping on synthetic data, the next steps will concern its integration in the neurosurgical procedures.

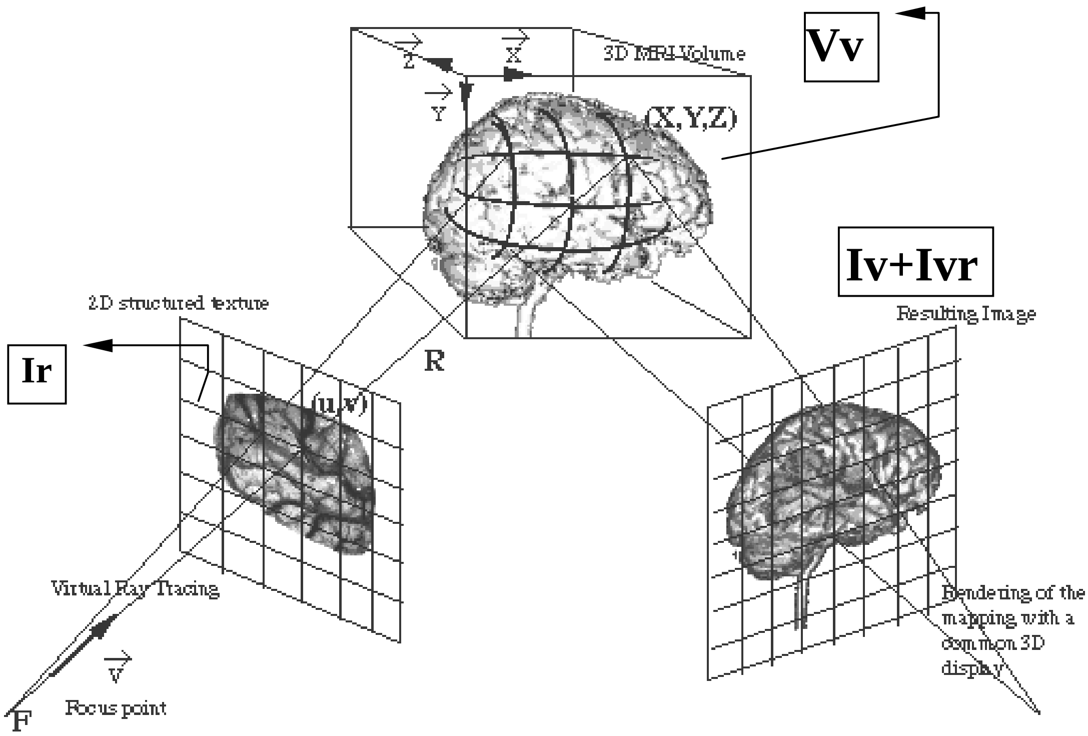
2. The “Virtual Ray Tracing” method

For the visual confrontation, we choose to integrate the real 2D images in the virtual world. We propose in this paper a new approach based on the mapping of a “real” 2D image of the anatomy of the patient on the virtual images. The problem corresponds to a texture mapping with the respect of the acquisition geometry. This method allows to compute the coordinates of all 2D points belonging to the photo in the 3D coordinates system. To do this, we need the computation of the 3D to 2D matrix corresponding to the rigid transformation which associates to a 3D point its corresponding 2D one on the photo. Once the computing of the 3D position (3D geometry) of the 2D capture is completed, the computing of new points of view of the 3D data set with the projected photo is automatically done. So, the problem is now to find or approximate the 3D shape of the photo with only 2D information.

No assumption about the shape of the area or about the geometry of the capture of the photography is taken in this method. In the first developments, we have tried to forget the applicative data and to have a global approach independent from this applicative context. The same problem could be find in realistic rendering of digital ground model, for instance.



The data of the application : the 3D display of segmented brain and the 2D picture



The different steps of this method are :

Data Pre-Processing to select the areas of interest,

3D to 2D Registration to compute the acquisition geometry of the photo,

Virtual Ray Tracing to retrieve the 3D information of the points belonging to the photography,

Rendering of the 3D data set and **Display** of the photography on the 3D virtual data set as a texture mapping.

Let **Ir** be the photography or 2D real image of the object,
Vv, the 3D synthetic data set or virtual volume,
Iv, the rendering or the virtual image of **Vv**,
Ivr, the resulting image of the projection of the 3D reconstructed photography.

2.1. Computing the acquisition geometry for the photography

So, we have to compute a 3D to 2D matrix. It's a classical registration problem where different methods[9][10][11] can be used according to the choice of a rigid or elastic transformation to model the deformation, to the referential data to match (point to point, set of points, surfaces, volumes or combination between them), to the computation of a criteria between the referential data (Euclidean distance, Champfer distance, ...) and to the criteria minimization or maximization function used to select the best solution (least squares, Powell algorithm, ...).

> The problem of the computation of a 3D to 2D transformation is common with the applications using directly this matrix to project the virtual data in a real photography or video; the fusion is done in the real world. In our case, we will use this matrix to find the 3D geometry of the pixels belonging to the photography. So, this fusion is done in the virtual world.

Our problem is to find the eleven coefficients of the following matrix :

(u,v) 2D point belonging to **Ir**,
(X,Y,Z) 3D corresponding point in **Vv**,

$$t\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} m_{11} & m_{12} & m_{13} & m_{14} \\ m_{21} & m_{22} & m_{23} & m_{24} \\ m_{31} & m_{32} & m_{33} & 1 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}$$

To perform this registration, we have used a simple point to point registration which needed the knowledge of 5 1/2 (6) points. The 3D data set is rotated according to an orientation close to the 2D picture one. This selection is done on both images by choosing common referential points. The conic transformation is computed by minimization (Least Square minimization method) of the Euclidean distance between the referential data. The corresponding matrix is then stored with the data[12].

2.2. Virtual Ray Tracing

A new method based on a "Virtual Ray Tracing" has been develop to allow the computation of the 3D information of **Ir** without any a-priori knowledge of **Vv** or of the capture geometry and without any use of 3D acquisition system (laser, 3D stereo vision or 3D sensor, ...).

The aim of this method is to retrieve the 3D information of **Ir**. The 3D to 2D matrix is not well-posed, so it does not allow us the direct computation of the 2D to 3D inverse matrix. So, we have to develop a method similar to the 3D reconstruction methods.

The basic idea is simple : Rays are virtually traced through the nodes of a grid defined on **Ir** to the volume **Vv**. The 3D coordinates of the 3D point reached by a ray are associated to the corresponding node of the grid. This 3D point also corresponds to the intersection between the ray and the object surface. So, for all nodes of the grid, the 3D coordinates in the **Vv** coordinate system are computed. After this step, the picture will be represented by a 3D surface constituted of polygons. This surface can be rotated and projected as wanted in the **Iv** coordinate system used for the display of the 3D volume.

2.2.1. Equation of the straight line corresponding to a ray

So, for each node (u,v) belonging to the 2D picture **Ir**, we have the equation giving the 3D coordinates (X,Y,Z) in the **Vv** coordinate system (C.O.S.) related to (u,v).

$(X,Y,Z) \in \mathrm{V}v\,\mathrm{COS},\ (u,v) \in \mathrm{I}r\,\mathrm{COS}$

$$t\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} m_{11} & m_{12} & m_{13} & m_{14} \\ m_{21} & m_{22} & m_{23} & m_{24} \\ m_{31} & m_{32} & m_{33} & 1 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}$$

This 3D to 2D matrix gives us the following information :

$$(m_{11} - m_{31} * u) * X + (m_{12} - m_{32} * u) * Y + (m_{13} - m_{33} * u) * Z + (m_{14} - u) = 0$$
$$(m_{21} - m_{31} * v) * X + (m_{22} - m_{32} * v) * Y + (m_{23} - m_{33} * v) * Z + (m_{24} - v) = 0$$

These two 3D equations correspond to the equation of a 3D line (ray R, principal vector $\vec{V}$). The ray are traced from all the nodes of the grid belonging to the selected area in **Ir**.

2.2.2. First and end points of the ray

The volume is traversed by a ray going from :

- the intersection between the ray and the side of the bounding box (cube enclosing the volume) which is the closest to the projection center (focus point F),
- to the second intersection of the ray with this cube.

A reduced enclosing volume could be defined in order to reduce the number of points touched by the ray.

2.2.3. Stop condition

The ray path is stopped when we reach a point belonging to the selected volume or the end point. The latter case is an error case due to the fact that each point belonging to the selected area on the picture should have its corresponding point in the segmented 3D volume. Nevertheless, if a such point is encountered because of a bad accuracy of the 3D to 2D matrix computing, this point is removed.

2.2.4. Direction of the ray

If V_1 is the vector defined by the projection center F and the first point of the ray and V_2 the vector defined by the projection center F and the volume center, the direction of the path (positive or negative increase) is determined by $V_1 . V_2$.

2.2.5. Increase of the ray

To compute the 3D coordinates (X,Y,Z) of a point belonging to the ray, we fix the value of one of the coordinates. The two equations give us the two others coordinates as a function of (u,v). The fixed coordinate is the one which axis is closer to the ray principal vector $\vec{V}$ (i.e. maximal scalar product between $\vec{V}$ and $\vec{X}$, $\vec{Y}$ and $\vec{Z}$ main vectors of the volume coordinate system). This coordinate will be increased from the intersection point to the last point in the volume according to the path of the ray.

From all the nodes of the grid defined on **Ir**, a list of the polygons is built. For each of them, the following information is associated :

* coordinates of each vertex of the polygon in the **Ir** coordinate system and in the 3D **Vv** coordinate system,

* coordinates of the normal of the polygon in the **Vv** coordinate system computed with the 3D coordinates of each vertex of the polygon.

These information are stored in a file linked to the data set[12].

2.3. Display

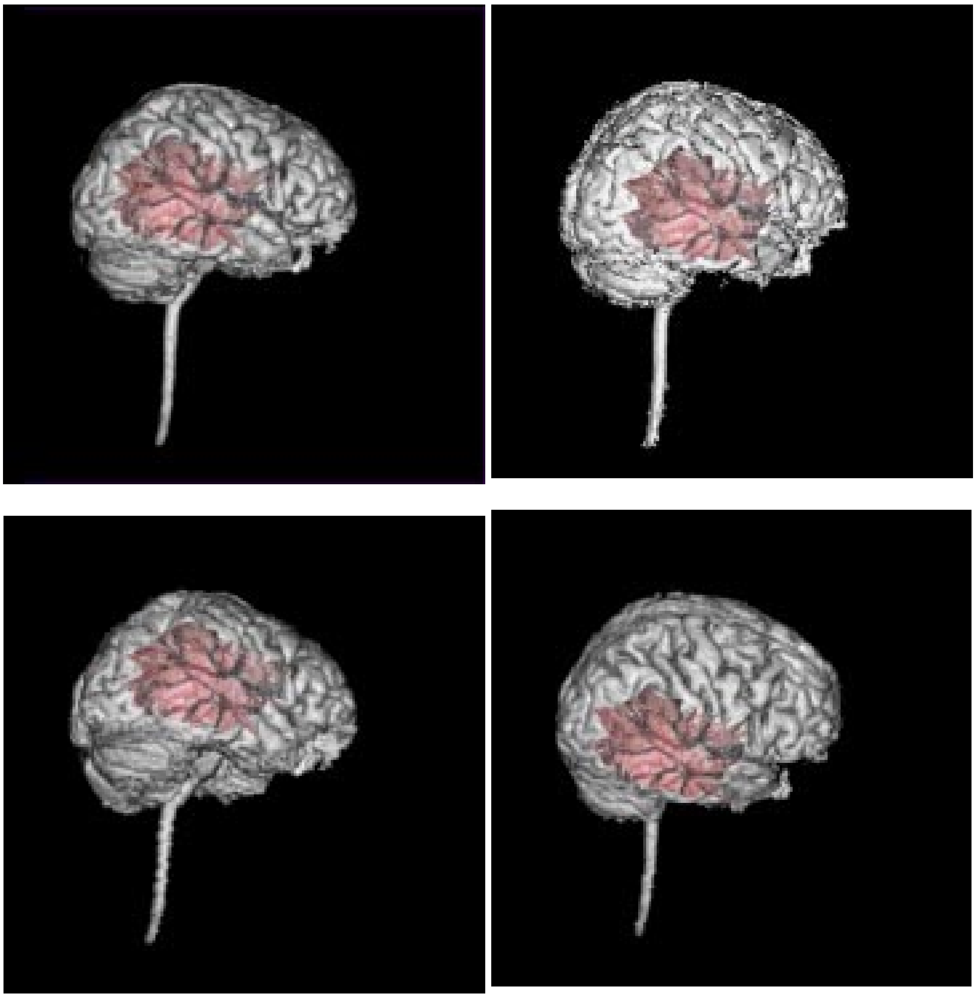
Once the 3D information related to the 2D picture is computed, we can display the result of the mapping. The picture **Iv** is first computed using any 3D rendering algorithm. Here, we use our own 3D algorithm which provide 3D good quality display with volumetric compositing rendering.

When a new point of view is needed, the following sequence is executed :

An image **Iv**, result from the projection of the **Vv** volume on the screen plane (3D data to 3D screen matrix : Mat_Volume_to_Screen), is computed.
Then, an image **Ivr** of the 3D reconstructed photography is computed according to this new orientation (Mat_Volume_to_Screen):
- The backward polygons are removed using classical scalar product between the normal vector of the polygon and the viewing vector.
- The vertices of the polygons are projected on the screen plane.
- The hidden pixels are then removed using a classical Z Buffer.
- The 2D projected polygons are filled using interpolation on the picture values.

Merging the images : The resulting image is computed by summation using transparency between the **Iv** and **Ivr**.

The rendering can be done with any kind of projection (conic, spherical, orthographic or whatever).



*Different points of view of the mapping of the 2D color picture **Ir** on the 3D data set **Vv***

3. Discussion

The aim of this preliminar study was to validate this virtual ray tracing method and the visual quality of the rendering. So, for the tests we have used data coming from the specific context of epilepsy surgery. The photo concerns the anatomical area visible after the definition and the resection. Brain, vessels, electrodes penetration points and operative field are viewed. This picture is taken with a DCS 400 Kodak, without any constraint, by the neurosurgeon in the operating room (OR). The size of this picture is 1532*1024 R.G.B. pixels.

The data are acquired on a 1.5 T General Electric Signa MRI related to a common T1 protocol provided 124 slices (256*256) (thickness : 1.3 mm.). Because real and virtual information must concern the same object(s), we must be able to segment the anatomical areas shown on the photography. The MRI data base is segmented on the brain surface using classification methods[13]. The user selects, manually with common 2D tools, the area of the digital picture he wants to map on the MRI segmented data.

3.1. First conclusions

Tests and results show the following conclusions about the "Virtual Ray Tracing" method.

This method is independent from :

- the registration method used for the computation of the 3D to 2D matrix,
- the 3D algorithms used for the rendering of the 3D volume,
- the capture of the 2D picture (any focus lenses, any distance, ...).

To validate the virtual ray tracing algorithm and the display, we used a simple registration method but we realized that the accuracy problems come from the 3D to 2D registration method :

- The accuracy of this system is very dependent on the designation of the corresponding points. We use the electrodes implantation points as referential data. These points are visible in the segmented MRI and in the 2D picture. However, it was difficult to accurately find these points in both modalities.
- The captured area on the picture corresponding to the cortectomy skull resection is small (5cm.*5cm.). This area is somewhat curved. So, the registration points are not very representative to the conic projection.
- No information or constraints related to the shot are used. So, the resulting matrix from the minimization method is only a consistent result but geometrically non reliable. Introducing constraints (focal distance, object-camera distance, ...) will make this computation more reliable. A new digital camera gives up now the acquisition parameters in a file linked to the picture.

The registration and the virtual ray tracing are performed once only for one volume and one 2D photography. The computation time is small (few seconds) but can be optimized (better enclosing volume, look-up table use, ...). The grid used on the picture can be reduce to a more significant number of polygons to a better resolution.

The rendering quality of the fusion is dependant to the angle between the viewing orientation and the acquisition one. This problem is common with all 3D reconstruction methods. The computation time for the display are also low (less than one second). The computation of the values of the picture projected on the volume is done in the picture coordinate system. So, this method takes into account the high resolution of the picture

(1532*1024). In the same way, the magnification is computed in the picture coordinate system.

3.2. Using this application

The superimposition (registration and fusion) of 3D morphological and/or functional data set with per-operative images is an important aspect of the neurosurgery of tomorrow. This approach is fundamental in a computer aided therapeutic planning (robotic instrument holder, 3D sensors, ...) and defines interactivity between standard modalities (MRI, CT Scan, ...) and the per-operative view of the anatomical objects. This mapping could provide different kind of application :

- the confirmation of a surgical strategy based on 3D data sets (MRI, CT, ...) with the real surgical data found during the act,
- the study of accurate correlation between the operative context before and after the operation,
- the real time superimposition of images viewed in a microscope with the 3D synthetic data to control the performance of the act on a TV set in the surgical room or for remote surgeons.

Dynamic sequences of images acquired by a digital camera or digitized could be also mapped on the brain surface. It can allowed, the brain deformation due to the cortectomy expected, the replay of the act or a part of it in a delayed-time display and with any kind of 3D point of view. The use of an optical system for 3D localization with the application should also allowed to be independent of the wearisome step of the selection of anatomical referential points between the 3D volume and the picture to be mapped. Moreover, this system could taken into account the low motions due to a new point of view or to the patient motion using markers attached to the patient.

3.3. Future works

The next steps are related to the automation and the improvement of some procedures of this method and related to its integration in an applicative context.

The 3D to 2D matrix computation problem must be take into account. The new digital cameras allow the knowledge of the acquisition information stored with the images. This information can be used to help the matrix computation. The use of 3D sensors will also facilitate this registration task. The camera can also be calibrated using phantoms, dividing the registration task into two parts : the computation of the 2D transformation relative to the camera and the 3D transformation relative to the patient's orientation and position.

4. Conclusion

This work is included in the research about the matching between 3D virtual images coming from anatomical imaging sources and real images. Generally, the problem is to create links between information coming from virtual world (3D computed images) and real world (patient, OR environment, surgical tools, stereotactic frames, ...)[1], but also to consider these real images as a new modality.

The complexity of the cerebral anatomy explains the interest of such methods in neuro-surgical fields. The improvements in this kind of applications will come from the results of the research in multimodal data fusion in which this work is inserted. The integration, in the surgical procedures, of tools attached to interventional imaging, to surgical act robotization and 3D localization will further the development and the use of technique similar as such presented in this paper.

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