USE OF OPTICAL MOTION TRACKING IN APPLICATION DEVELOPMENT FOR SURGICAL PLANNING AND NAVIGATION

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Abstract

This paper makes an overview of the application development in the field of optical motion tracking accomplished during the recent years in Hungary. The elements of the integration of known optical camera (passive Polaris, Northern Digital Inc.) into navigation studies are surveyed according to standpoint of software engineer: (A) creating a proper software architecture; (B) selection of calibration procedures for navigated tools and anatomical objects; (C) practical solutions for registering the surgical space to diagnostic models; (D) visualization of registered movements of objects in diagnostic volume. The presented procedures are based on two applications: (A) prototyping program to simulate complex navigational and measurement tasks occurring in clinical field (VocPC); (B) commercial application suitable to control navigated drilling in dental implantology (Dental Planner).

Keywords: optical tracking; navigation software; tool calibration; implant placement

Introduction

The application of modern 3D (3 dimensional) motion analysis methods in Hungary can be dated from the establishment of the Biomechanical Research Centre at the Budapest University of Technology and economics in 2002[8,9]. The foundation of this Centre was followed by establishing other biomechanical laboratories at the Semmelweis University in Budapest, Pécs University, and so on. These laboratories give full opportunity of movement analyis in different fields of clinical research: sport medicine, neurology, rheumatology and orthopaedics as well. Until now the collection of motion data is relied on video-based motion analyser and Zebris ultrasound-based systems.

From the mid 90-ies new technology offers commercial tracking systems on the field of optical motion analysis. These devices are flexible enough to use them not only for clinical motion analysis but in surgical navigation as well[5,19]. The passive optical sensors provide for **wireless** measurements of 3D location/orientation parameters of rigid bodies with reasonable accuracy (~0.3 mm RMS). The worldwide spread of the optical technology is pioneered by Northern Digital, Inc. (NDI, *www.ndigital.com*) which developed the Optotrack and Polaris families of cameras. They have no sensitivity to temperature and noise from sound sources when compared to Zebris JMA ultrasound systems *(www.zebris.de)* and the sterilization is manageable (for illustration see *Figure 1*). From the early days a large increase can be seen in the number of clinical applications. Unfortunately the Hungarian participation on related international conferences (CARS, *www.cars-int.org,* MICCAI, *www.miccai.org,* etc) is still very limited. This can be a consequence of large expenses of development but also related to an unexplainable omission of this field. Our effort is to make progress in application development by integration of NDI Polaris camera into surgical navigation studies. To reach this goal two approaches have been accepted and pursued:

1. creating a general purpose framework for navigated graphical environment which can be compared to real images of anatomical objects[2,13,16],

2. developing commercial application for a special field of image-guided navigation, the implant planning and navigated surgery in dental implantology[12,15,17,18].

Both approaches reserve major challenges for software developer. In case of 1, the goal is to develop a general-purpose interactive software module for run-time planning and execution of surgical planning and navigational tasks. The software has the capability to interactively create and modify the internal, coded representation of a virtual environment which is compared to real images of anatomical objects. The known frameworks for graphical design (for instance Open Inventor, Silicon Graphics, Inc.[10]) have a great potential for creating high quality 3D scenes but less suitable for organizing the functional units of navigation (surgical space registration, sensor-based tool calibrations, reference sensor switching, anatomical space calibration, target point optimization, etc). The suitable architecture of 3D virtual environment is based on procedures known from data manipulation in tree structures of nodal topology[11]. The navigation elements, which are derived from a common navigation object, are able to refresh the local (relative to its parent) and global position/orientation (relative to the root space of camera) values according to tree hierarchy and also able to perform specialized configuration interaction. The prototyping approach meets the demand of creating one single software environment for both the preoperative planning process and the intra-operative intervention.

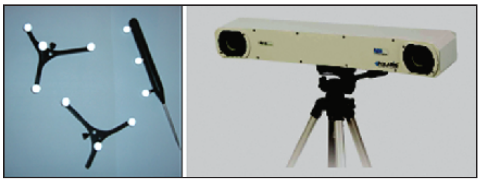

Figure 1. The key hardware elements of the optical motion tracking systems (left: rigid bodies or sensors with reflective sphere markers; right: twin-camera for marker detection)

The experience from framework studies can be utilized in developing specialized, commercial applications. However, this work evokes other difficulties: need for strict reliability, accuracy, ease of use, graphical quality, speed etc. As a compromise for limited resources for development and the chance for success, the computerized dental implantology was selected for commercial application. The program is available now in Hungary and offers 3D implant planning and navigated drilling for implantologist with much lower cost than any foreign competitors.

Unfortunately, the investment potential in Hungary is very limited into this direction. It seems that, in spite of the available brain power, the expensive import is preferred and the local initiatives of the qualified engineering work are neglected. Looking into the overwhelming number of presented materials in international conferences (mainly from Japanese and German teams), the institutional and private investments into this area are urgently needed at every level of clinical research and commercial applications.

Methods

Framework development

The application interface consists of three main parts: (A) viewer slots for displaying the diagnostic data and movable graphical elements; (B) navigation tree with context menus for configuration of tree elements; (C) observer slots for numerical display of relative location/orientation and distance values in the tree during motion *(Figure 2)*.

The program is able to archive the navigation topology and recall it for use later with motion tracking turned on. The topology is built up from a root space ("3D Space") which represents the global space of the motion tracking camera. The tree objects are connected by nodes. The projection transform between any pair of representative coordinate spaces can be easily calculated according to tree hierarchy. Three slice "Viewers" or virtual cameras (axial, sagittal and frontal) and one surface Viewer (for surface rendered data) can be inserted into the space of diagnostic volume. This volumetric model is based on the slice sequence from CT (computer tomographic) or MR (magnetic resonance) imaging and can be located within the coordinate space of an attached sensor to define a movable reference volume. The relocation, insertion and removal of any tree element (and the attached subtree elements) are possible (with some exceptions) and the results of these interactions are made visible in the viewers. Sensor elements can be added anywhere to the topology considering that sensors are functioning under **global lock** i.e. refreshing always their location/orientation values relative to camera or root space and not to their parent's coordinate space. Northern Digital offers a valuable software package (6D Architect) which can be used to create rigid body sensors of individual geometry.

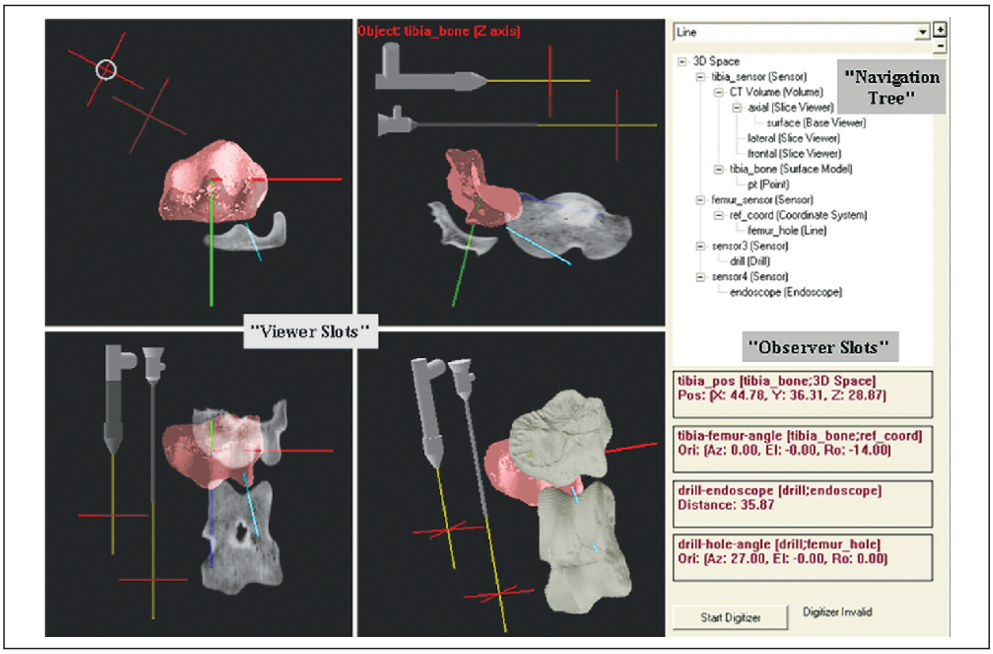

Figure 2. The main navigation panel. The volumetric and surface models are created by two ways: isosurface reconstruction (bottom right, grey) and triangulated mesh reconstruction (bottom right, pink) following the CT imaging of pig's knee joint. Several navigated objects (surgical tools, pointer) and graphical elements (points, lines, coordinate spaces, imported mesh surfaces) can be involved and organized by navigation tree. The Viewer Slots assignments: raw axial CT data (top left); resampled sagittal (top right); resampled frontal (bottom left); isosurface rendered (bottom right)

Navigation objects

The navigation tree is a hierarchical tree structure containing all the navigation objects existing in the 3D space of navigation. These objects can be of many types but their common properties are that they all have their local coordinate system. This coordinate system is defined by its position and orientation relative to parent's space giving to all objects of navigation space the 6 degrees of freedom. The nodal hierarchy gives the ability to efficiently determine the linear transformations between two navigation objects and this structure can be altered interactively. The transformation is defined between the local space and parent's space according to the floating axis Euler convention. Each navigation object can be locally positioned and reoriented and in the same time appears as an element of nested transformations in the tree. Two possible consequences of relocation are considered: (A) the relocated object preserves the local position/orientation to its parent or (B) it keeps the global location/orientation relative to the root space of camera. The second case is called as "global lock" and is important when the parent's space should be changed with keeping the global coordinates and orientation unchanged ("reference sensor switching").

Tool calibration and surgical space registration

Navigation objects are extended with functionalities which can be configured individually. These are: (A) the volume navigation object which can be registered from a sensor space; (B) the coordinate space object which has an option for calibration to the attached sensor space (anatomical space definition); (C) surgical tool navigation objects (drill, endoscope, biopsy needles) which have sensor-based calibration algorithm[3]. The tool calibration provides for tip offset and axis direction values relative to the space of an attached motion sensor. The feature points for registration and calibration procedures are collected by the pointer of the Polaris system. The results of these configurations are location/orientation values and easily interpreted in the navigation tree.

Commercial development

Our intention was to develop an easy-to-use implant navigation system for computerized dental implantology[14,15,17].

The planning tools follow the known, standard methods of this field: (A) CT imaging (visualization with volumetric and surface rendered models); (B) volume resampling (interpolation of images with non-standard slice directions) for panoramic and transversal views according to the jaw curve; (C) localization of virtual implants in 3D. Future trend in computerized dentistry predicts more use of 3D visualization of anatomy (laser scanning of topography and various surface reconstruction techniques). Direct visualization of anatomy during surgery revives wider use of active navigation. The presently available foreign methodologies in Hungary offer only template based approach. They support implant placement with manufacturing drill guiding templates. The whole procedure can take weeks to finish. Our application supports active navigation suitable for intraoperative use. The navigated drilling can be started in a navigation panel which incorporates tool calibration and tracker's space to CT registration capabilities *(Figure 3)*. After validating the navigation settings the user can follow the movement of a dental handpiece in registered 3D scene with optionally viewable elements like implant models, nerve models, tooth models and background surface image reconstructed from patient's CT.

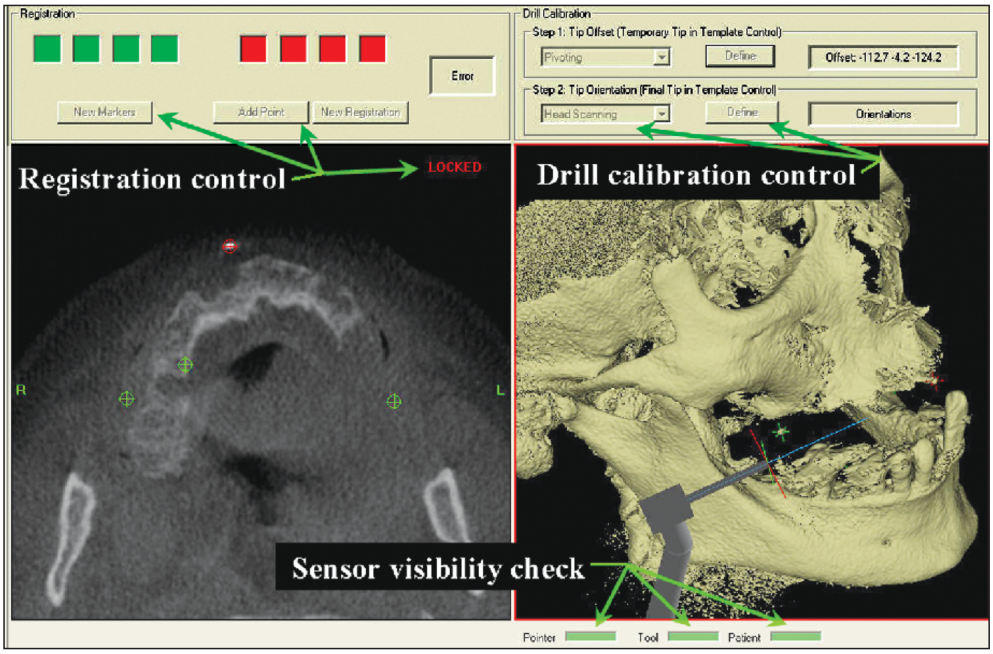

Figure 3. Controls in the navigation panel of the dental program. The registration procedure is marker-based with an accuracy in the range of 0.3 to 0.6 mm

Results

Framework studies

The prototyping program has been tested in several experiments but we are still in need of meaningful clinical applications. *Figure 4* illustrates the navigation view of a cadaver experiment which has a reference sensor on the femur part and tracks the motion of tibia by displaying the movable polygon surface (pink). First, the user registers the Polaris space to CT volume through markers placed on femur. After it the tibia model can be aligned to the actual position by defining anatomical coordinate space (or marker points) both on the model and on bone (relative to an attached sensor). Following this initialization, with motion tracking on, the investigator can make numerical analysis of movement path of any point of tibia relative to (movable) femur reference. Feature points can be placed on the surfaces (as the child objects of the surface own coordinate space) and with the help of navigation tree and observer slots the distance and angular values of relative movement can be easily recorded. Moreover, clinically feasible movement path of surgical tools can be tested and visualized.

Dental studies

The dental navigation system – according to the present trends in computerized implantology – is able to support the intraoperative, active navigation and template-based navigated drilling as well. Both methodologies have their own field of applicability in clinical practice. Specific surgical template with **four metal markers** is fitted to the patient mouth at the time of CT scanning. In our case the surgical space is registered to the CT volume – which contains the treatment plan – through these markers. The surgical template can be supplied with guiding cylinders for the surgeon's drill. After registration the implant surgeon is able to prepare the template with high precision which guides the drill to the planned position. Alternatively, the template – with an attached sensor to detect the patient's movement – can be placed into the mouth during surgery. In this case the template serves as console for the sensor, holds the markers and supports direct navigated drilling with an appropriate moulding. The rigid, accurate fit of template can be fixed by three screws to the jaw bone which are planned similarly to the implants. *Figure 5* and *6* illustrate the planning and navigation phases of the software control, respectively.

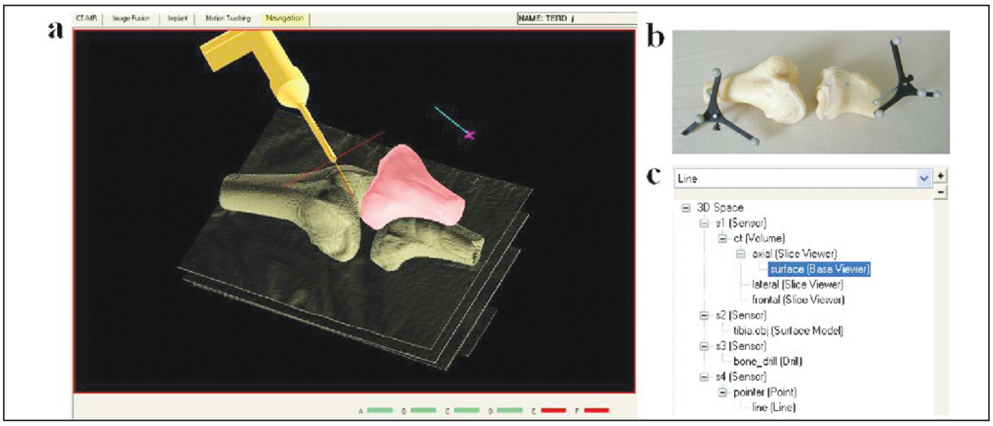

Figure 4. Framework application. Illustration of a cadaver experiments based on movement recording of tibia relative to reference coordinate space set on the femur. The movable model of tibia is created from the isosurface rendered model by suitable surface reconstruction algorithm (a). The sensors are attached to the bone parts (b) and the topological relationships are planned by the navigation tree; the experiment needs two more sensors to track movements of the pointer and drill (c)

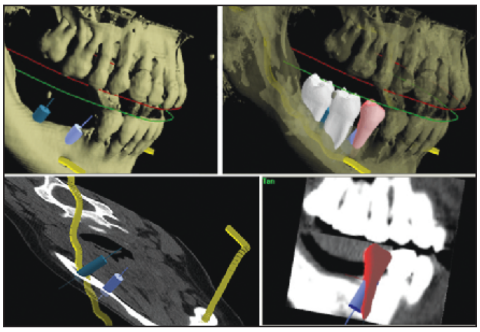

Figure 5. Dental application. Different scenes illustrating the functional and anatomical elements of planning such as: use of dental database for estimating interocclusal contacts between the upper and lower jaws (right views); virtual implant placement in different views for full 3D control (left views); nerve modelling (left bottom)

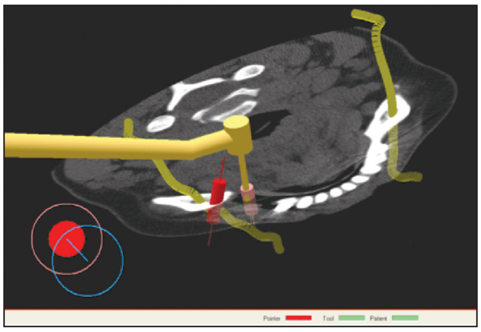

Figure 6. The virtual scene of handpiece navigation in computerized implantology. It prepares the placement of dental implant into the lower jaw. Targeting aid can be seen in the left bottom corner. The same visualization can be used during intraoperative navigated drilling of jaw bone or template preparation for drill-guiding holes

Discussion

The recent results of the application development with an optical motion tracking camera have been presented. The optical system has some advantages and disadvantages when compared to ultrasound-based system. It has wireless, flexible sensor configurations which can be sterilized. The motion tracking is temperature independent. All of these make it very suitable for surgical applications. However, the error of local 3D measurements can be 2 or 3 times larger than with the Zebris JMA system. Complex applications (with added error components of registration and tool calibrations) modify the final error value for both systems but our experience shows that the critical limit of 0.8–1 mm for surgical navigation is complied with NDI Polaris camera. The accuracy of kinematic measurements can be improved by the point cluster technique with special sensor geometry which is detected by NDI 6D Architect or self-written software[1].

A general purpose software framework was developed which is usable to solve 3D graphical prototyping tasks for surgical planning and navigation. The proposed methodology adopts the known rules of nodal topology in hierarchical tree structures and converts those into the practice of software design in medical field. Similar approach to design software architecture for surgical planning has been already described in[4,6,7] with some differences to the present application. The system developed in[6] has the same nodal topology to build up the graphical environment but it does not integrate smoothly the important elements of navigation (registration objects, sensor-based tool calibrations). On the other hand, they are able to add live video view very efficiently (with special distorter/undistorter functionalities for endoscopy). They also realized that extendable frameworks are needed to bring the actual computer-aided preoperative planning scheme into the operating room[4,6].

The experience with the framework development helped us to create a commercial application for a specialized field: the image-guided implant placement and navigation in dentistry. Computerized dental implantology is a very vivid area worldwide because of sharp increase of implant surgeries. However, until now only the Swedish Nobel-Biocare offered software and technology in Hungary for the template-based implant placements but not for active navigation. Our application has software tools for controlling motion tracking devices during active navigation. Future trend in computerized dentistry supports this because less use of CT or DVT (digital volume tomography) imaging and more use of 3D visualization of anatomy (laser scanning of topography and various surface reconstruction techniques) are expected. Direct visualization of anatomy during surgery revives wider use of active navigation. Our system gives a good chance to have a cheap alternative for a wider introduction of advanced dental implantology in Hungary.

Conclusion

An overview of application development in the field of optical motion tracking is given. The elements of the integration of known optical camera (passive Polaris, Northern Digital Inc.) into two applications are surveyed: 1. framework application designed for prototyping and testing surgical navigation tasks, and 2. specialized application on the field of dental implantology.

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