EndoCAS navigator platform: a common platform for computer and robotic assistance in minimally invasive surgery

Giuseppe Megali[1]*, Vincenzo Ferrari[1], Cinzia Freschi[1], Bruno Morabito[1], Filippo Cavallo[1], Giuseppe Turini[1], Elena Troia[1], Carla Cappelli[1], Andrea Pietrabissa[1], Oliver Tonet[2], Alfred Cuschieri[2], Paolo Dario[2], Franco Mosca[1]

[1]*EndoCAS Center, Universit`a di Pisa, Italy*

[2]*CRIM Lab, Scuola Superiore Sant'Anna, Pisa, Italy*

Introduction

The revolution of minimally invasive surgery (MIS) with respect to conventional open surgery necessitated initial changes in the surgical instruments: the terminal parts of traditional surgical instruments were miniaturized and placed at the end of a rigid stem, so that they could be introduced into the body through small ports. Commonly used instruments for MIS are passive and the surgeon must himself deal with all the workspace and sensory limitations (1) that are the inevitable adverse consequences of MIS. Consequently, the surgeon has to learn new operative skills to change from a traditional to a minimally invasive surgeon (2). New technological tools (3,4), based on image guidance (5–7), robotic (8,9) and mechatronic (10,11) principles, have been developed to assist the surgeon and enhance his dexterity and perception. The features integrated in these tools, such as sensors and fine positioning capabilities, provide a solution to the problems related to tactile perception, dexterity and precision of intervention. Restoration of orientation and depth perception and assistance in positioning and trajectory execution can be achieved with the integration of traditional and mechatronic surgical tools into augmented reality systems (also called 'navigation tools'). Currently there are commercial CAS systems only for orthopaedics, neurosurgery and ear, nose and throat (ENT) surgery (12) and for few other surgical applications (13). Several research groups are developing specific CAS applications and others are implementing nondedicated software platforms (14–17). The aim of the present work was to develop and implement a highly modular software/hardware platform suitable for CAS, and to produce a prototype demonstrator to document its potential for clinical application in laparoscopic surgery. By integrating pre-operative images, intra-operative data and information provided by the sensors mounted on the surgical tools (or integrated in them), the EndoCAS Navigator Platform enables: 1. Intuitive diagnosis and natural communication between radiologists and therapists by means of 3D visualization of medical datasets. 2. Intuitive planning of the surgical procedure by means of virtual navigation inside the human anatomy. 3. Computer guidance by augmenting reality during the intervention using traditional tools. 4. High-precision positioning of tools, manually or by means of robotic arms. The objective of our research was not to build a universal system that could deal with all the problems of any application. However, since many applications pose very similar problems, we defined a general CAS concept that encapsulates basic tools and provides to final users (surgeons and radiologists) real and usable demonstrators which, according to our experiments, simplify communications between the developing engineers and the clinical users and help them to appreciate how state-of-the-art technologies can be used to proficiently assist and enable their work. This is important, as clinicians have to be the prime movers of the development process.

Materials and Methods

EndoCAS navigator platform overview

In the system design, the objective has been the realization of a generic architecture, comprehensive of all features necessary to a system designed for assistance in surgery. The approach adopted is based on the concepts of modularity, compatibility and incremental feature composition. The system architecture integrates aspects of augmented reality, computer-assisted intervention and medical robotics into a modular open environment. The architecture has been defined in terms as generic as possible, taking into account the growing needs for information technology in surgery. At the current stage, the platform consists of a working demonstrator incorporating generic functions, tools and modules commonly employed in surgical assistance. Specific applications can be constructed by simply assembling different components, and by developing only the functions necessary to a specific application.

Functional description

From a functional point of view, the specifics of the platform are illustrated in Figure 1 (left). The scheme highlights the communication between the main functional modules of the system and the interaction between system, surgeon and patient. The platform consists of three main functional modules: the surgical tools, the main processing unit, and the human–machine interface. The *surgical tools* module comprises the instruments used to perform the interventions. We classify these into *traditional tools* and *programmable tools*. Tools commonly used in surgical practice and managed by surgeon in a traditional way fall in the first category. These tools, used for imaging (laparoscopes, ultrasound probes, etc.) and intervention (scalpel, forceps, cauterizer, drill, biopsy needle, etc.), are passive with regard to movement control and work under the direct manual control of the surgeon. In contrast, the programmable tools category encompasses active, smart tools (such as mechatronic and robotic tools) provided with sensors and programmable actuation capabilities. The *main processing unit (MPU)* processes and integrates *preoperative data* with *intra-operative data* concerning the surgical environment and the internal status of the programmable tools. Integrated data (provided by the *data fusion and registration* module) are processed by the *cognitive unit* and returned to the surgeon in form of sensorial enhancement by means of the *human–machine interface (HMI)*, which comprises two modules that can function independently: the *visual user interface (VUI)* and the *haptic user interface (HUI)*. The status of both interfaces is updated in real-time. The surgeon interacts with the programmable tools through the HMI. The cognitive unit, integrating commands given on the HMI with the information provided by the MPU, provides for visual safe guidance and monitoring dangerous situations that may occur during navigation (i.e. contact, proximity, etc.) and acts as an intelligent and active filter to the programmable tools commands given by the surgeon, inhibiting or reinterpreting the most critical ones. The synergy between system and surgeon is achieved by means of the cognitive unit, which, by implementing a closed loop between surgeon's commands, programmable tools and MPU, enhances overall performance.

Implementation

Based on the functional approach described, we implemented an integrated system for computer assistance with in-built extreme versatility, enabling the selection of the appropriate components for specific applications. The system can be used for pre-operative visualization, diagnosis and planning, intra-operative passive and active guidance. Furthermore, the system integrates components such that it is capable of adaptation for a variety of application domains. The integrated system is illustrated in Figure 1 (right), which highlights the hardware and software components and their intercommunication. The availability of virtual models of all relevant elements in the surgical scene is a pre-requisite for the construction of the *virtual environment*. Medical images of the patient are acquired pre-operatively (*image acquisition*). Volumetric data are treated by a *modelling* process in order to build realistic geometrical virtual models of the anatomical organs and structures (*virtual anatomy*) involved in the intended operation. Virtual models of the surgical tools (*virtual tools*) and of all devices that will interact with the patient are generated using a CAD drawing program (*CAD program*). During the intervention, in order to place the elements correctly in the surgical scene, real-time information about their spatial position are provided by the *localizer*. The different reference frames in which spatial coordinates are described need to be co-registered and aligned with the virtual representations of objects (*registration*). The geometrical description of the surgical scene is enhanced by information derived from intra-operative imaging devices (*laparoscope, US-grapher*) and data collected by different types of sensors. All these datasets are integrated into the virtual environment by a *data fusion* process. This augmented reality is rendered to the surgeon through the HMI. The control loop implemented in the core of the *MPU* (*cognitive unit*) monitors the virtual environment and is responsible for determining the feedback actions associated with the state of the virtual environment.

Modelling of anatomical structures

The first phase of the 3D model generation procedure is the process of *segmentation and labelling*. This process consists in subdividing the volume in separate elements (*objects*) and then unambiguously assigning each volume unit to an appropriate anatomical structure (*object mapping*). To switch from the images to the *object map* (Figure 2b), we apply a process sequence (*pipeline*) to each *object*; this pipeline can be summarized as follows: 1. The enhancement of image quality, using contrast operators, histogram analysis and convolution filters. 2. The isolation of interesting anatomical parts, using thresholding, region growing (18,19) and active contours (20,21). 3. The volume smoothing of the interesting anatomical components, using volume operators as erosion and dilatation. Surface-based techniques are used to visualize in real time a 3D virtual environment. A processing pipeline has been implemented for automatic generation of 3D models from segmented volumetric datasets (Figure 2c). The pipeline has three stages: 1. Surface extraction from *object maps*, based on the *marching cubes* (22,23). 2. Geometric features enhancement, based on decimation (24), smoothing and refinement algorithms. 3. Texturing, based on material and luminance properties and textures. Virtual environments are created by integrating in the same view both extracted surfaces and original volumetric datasets (orthogonal slices). The visualization module, developed using the open source framework OpenSG (25), allows the visualization of virtual environments, modification of the virtual scene settings (transparency, slice position, organs to be visualized), performance of virtual navigation inside the patient by moving the viewpoint by means of a 6D mouse, and perception of stereoscopic images by means of a head-mounted display (HMD).

Localization

Localization systems allow real-time tracking of the position and orientation of moving objects (such as surgical tools, robotic arms and patient) and to realize interactive navigation systems that augment the information for the surgeon (using virtual and *mixed-reality* techniques) and enhance his/her performance (using robotic devices for accurate positioning) during the intervention. Both optical (Optotrak Certus∨, Northern Digital Inc.) and electromagnetic (NDI Aurora∨, Northern Digital Inc.) localization devices (26) have been integrated in the platform, for external-body and internal-body localization, respectively. We developed a software module on the top of the application programming interface (API) of the localizers that provides a unique interface to configuration and management functions, and allows the use of both in the same application. The module also implements methods for calibration of localization sensors with respect to tool shapes and functionalities. Specific procedures have been implemented for automatic dynamic calibration of sensors mounted on the surgical tools, and for manual calibration based on the digitalization of reference points on the tools. Other calibration procedures concern the robot-localizer calibration, and intraoperative imaging devices calibration (such us laparoscopic camera and US probe).

Robot arm

In the platform, an industrial robot (Samsung FARA AT2) has been integrated to provide active surgical assistance and accurate positioning during intervention (27). The robot reference system has been calibrated with the global reference system (given by the optical localization system), so that the robot can be moved along planned trajectories in a closed loop with the surgical navigator. We implemented an automatic iterative calibration method, based on the Lie algebra (28), to be performed at the beginning of surgical intervention and every time the relative position between the robot base and the localization system changes. Since the use of the robotic arm is limited to only few steps of the surgical intervention, we implemented a mechanism, based on a six degrees of freedom (DOF) force sensor (Mini45, ATI Industrial Automation Inc.) mounted on the end-effector of the robotic arm and on an admittance controller, that allows the surgeon to move the robot (in and out from the surgical scenario, or to a precise position) just by exerting force at its distal part.

Registration

The 3D virtual models, generated from the medical datasets, are aligned with the real patient position in the operating room by a registration procedure (29). We implemented a rigid registration method based on artificial markers and anatomical reference points. All triples of fiducial markers were registered using the optimal registration algorithm (30) based on SVD that optimizes the least squares of fiducial registration error (FRE) (31). Specific application studies have been done for the evaluation and limitation of errors introduced by using this registration method for surgical interventions that involve deformable anatomical structures.

Mixed reality

We developed a module that provides basic functions to implement *mixed-reality* solutions in different scenarios. Mixed reality, fusing real-world elements (such as images or video) with virtual synthetic elements in a single view, enhances visual perception and provides a useful support in both the diagnosis and the surgical intervention phases (32,33). The module implements two main functions: the *video acquisition and streaming function* that manages the image capture from a generic local or remote video source, and the *mixing function* that synthesizes the hybrid image using video frames and virtual 3D models.

Human machines interfaces (HMI)

We developed modules to integrate 3D visualization interfaces and haptic interfaces. We integrated localization sensors and two cameras aligned with the user eyes on the HMD. In this way we can provide a 3D visualization of the virtual scenario restoring the depth perception; change the viewpoint by simply moving the head; aligning the real with the virtual viewpoint, implementing a 3D mixed-reality that fuses in the same view the real and virtual information. Specific software modules have been developed for the integration of the general purpose haptic interface in the platform, and the implementation of closed loops with the robotic arm and the virtual environments.

A practical case: EndoCAS laparoscopy navigator

We developed a navigation system for laparoscopic abdominal surgery (Figure 3) providing preoperative and intraoperative assistance. Figure 4 shows the graphical user interface (GUI) of the system. The system allows the surgeon to study the patient anatomy in a preoperative phase, by means of virtual reconstruction generated from medical images. During the surgical intervention, the surgeon can benefit from preoperative information aligned with the real patient position. The system architecture has been created by involving some modules on the top of the previously described platform (Figure 5). Specific methods and customizations, described in the following subsections, have been implemented in order to fit the requirements of the laparoscopic application.

Results

3D modelling module

In collaboration with radiologists, we defined and developed an efficient segmentation protocol that allows the creation (in about 30 min) of 3D models of abdominal anatomies (bones, kidneys, pancreas, spleen, abdominal aorta, portal vein, splenic vein and cava vein) from medical datasets (34). The procedure uses ‘multiphase’ medical datasets consisting of several volumetric images of the same anatomical district, acquired with different delays from the injection of contrast medium (i.e. composed of more than one post-contrastographic phase). We adopted an ‘anatomy-driven’ segmentation approach, consisting of several steps: the registration of the different phases (in order to compensate variations in patient set-up during the acquisition of the multiphase dataset); the identification of the most suitable phase for the segmentation of the specific organ; the definition of the segmentation order of abdominal organs; and the definition of a specific segmentation pipeline for each organ (consisting of applying ad hoc parameterized algorithms for image filtering, thresholding, region growing and morphological operators). Each anatomical part is segmented using a specific processing pipeline that we developed as a stand-alone module on the top of the open source software ITKSNAP 1.5 (35,36). The optimal segmentation sequence, defined on the basis of our experience and on the basis of anatomical, empirical and functional considerations concerning the timing of contrast distribution, is given in Table 1. Names of phases indicate where the contrast medium is mainly localized during the dataset acquisition. Organs, extracted from the phase where they are better visible, are segmented using neighbourhood connected region growing. This algorithm, which considers the intensity of the neighbourhood voxels on the basis of a chosen radius, allows the avoidance of erroneous growing through small vessels or channels created by devices artefacts that join adjacent anatomical structures. Structures easy to segment (i.e. clearly identifiable on the images) are extracted at early stages of the segmentation process, and then removed from the dataset. This simplifies the segmentation of structures more difficult to identify (Figure 6) and the tuning of parameters for the region-growing algorithm. To compensate breathing and physiological movements, segmented objects can be dilated before removing them from the dataset.

Tracking module

We sensorized, and integrated into the system, rigid surgical tools commonly used in laparoscopic surgery (the laparoscope and the Harmonic Scalpel⌄, Ethicon Endo-Surgery Inc.), and a cutaneous digitizer designed to allow to the surgeon easy and precise digitization of artificial markers on the patient skin for registration purposes (Figure 7). We created infrared LED (IRED) supports and the cutaneous digitizer by means of CAD–CAM technologies. Using a reverse-engineering process, we designed inlaid interfaces of the IRED supports with surgical tools, and manufactured them by means of rapid prototyping. The developed devices (IRED supports and the cutaneous digitizer) are sterilizable, separately from other surgical tools, with ethylene oxide, and can be mounted easily during the intervention. The localization module allows to track the tip of surgical tools with a precision of about 1 mm.

Mixed-reality and camera calibration

Mixed reality view has been integrated in the system. This view, overlapping in real time the projection of 3D anatomical models of the patient (extracted from the medical dataset by means of the 3D modelling module) on endoscopic standard images, allows occlusion problems that occur using only the real images (that can visualize just-exposed surfaces) to be overcome and enhances the perception of the workspace during laparoscopic interventions. To implement mixed reality. we need to provide a virtual model of the real camera and its movements. Internal parameters of the real camera (the laparoscope) have been computed using the *pinhole camera* model and acquiring images of a grid (with known shape) in different positions (37). These parameters (field of view, CCD pixel dimensions, centre of projection and distortion, coefficient of radial distorsion) have been used to characterize the virtual camera and to correct the radial distortion of the laparoscopic image used as a background texture in the mixed reality scene. To reproduce coherently the real movements of the laparoscope in the virtual environment, a calibration method, that solves the geometrical problem described in Figure 8, has been implemented. The calibration matrix (*Tc*), representing the relative position of the camera viewpoint with respect to the sensorized frame, has been computed using a calibration grid sensorized with IRED. The transformations *T1* and *T2* are given by the localization system, while the transformation *T3* is determined using a computer vision method (38) that allows objects with known geometry (the sensorized calibration grid) to be localized in the camera reference frame. The alignment error between the real image and the virtual image has been evaluated by positioning the calibration grid (160 × 160 mm) perpendicular to the laparoscope point of view and at a distance of 150 mm. Under this experimental condition, the maximum displacement between the four corners of the grid in the real image and the corresponding points on the superimposed virtual image has been measured at about 2 mm.

Registration module

To reduce the registration error due to the use of a rigid registration procedure, the patient position during the acquisition of the medical dataset is the same position as he/she will have during the intervention. To determine anatomical landmarks to be used in registration and to estimate the influence on the registration error of the patient repositioning and breathing, we analysed abdominal surgical interventions (34). Based on anatomical and technical considerations, 18 active IREDs have been posed on specific anatomical points reachable during laparoscopic intervention on the skin of a subject, in the positions shown on Figure 9. From the analysis of data, three points (the right and the left anterior superior iliac spines and the upper sternum) were quite steady during breathing and only marginally influenced by patient repositioning. Using these points as fiducials for marker-based registration and the remaining 15 as potential targets, we evaluated the maximum single-point error on the patient skin. Averaging breathing movements, the medium square 'static error' on all markers target registration error (TRE) was 2.85 mm, while the maximum error was 6.02 mm. Without averaging breathing movements, the maximum error was 13.3 mm and this can be considered an upper limit for internal organs registration error during breathing. In fact internal organs do not move more than the external surface, since they are passive elements enclosed between the diaphragm, which has a maximum excursion of about ±7 mm (39), and the abdominal surface, where experimentally we found a maximum excursion of ±7.5 mm. Nevertheless, it cannot be defined as the 'expected error' because it does not consider some other relevant error sources (such as organ shifting) that require intraoperative imaging for evaluation. To evaluate organ shifting introduced by the repositioning of the patient on the operative bed, we used an US image device sensorized with IRED for position tracking. Combining spatial information provided by the localization system and by US images, we measured the position of internal anatomical target points that are easy to identify on the US image (i.e. low tip of left and right kidneys, vessel bifurcations in the spleen and in the liver, iliac artery bifurcation). Measurements, performed by repositioning the patient 10 times on the operative bed and at the same breathing phase (exalation), have been done in a reference system fixed to the patient body and defined on the top of the artificial markers used for registration. The maximum error on target points has been about 13 mm. This value (very close to the registration error measured on the patient skin), representing an estimation of the 'global expected error', is compatible with the precision required by our surgeons (about 20 mm) for the navigation system.

Discussion

Initial clinical experience

The system has been used for preoperative dataset visualization and surgical planning in more than 10 interventions and has been used inside the operating room to perform a laparoscopic distal pancreatectomy. The 3D reconstruction of the anatomical structures proved to be a very useful aid for preoperative surgical planning, providing to the surgeon a complete knowledge of the patient's anatomy. The surgeon orientation during the intervention was enhanced by virtual views that allow inspection of the surgical field from various viewpoints. Mixed reality view is also very useful in approaching the target of the intervention, providing the same benefits as a GPS system for car drivers. The integration of the navigation system in the OR did not cause discomfort to the surgical staff, had no material effect on the duration of intervention as a result of the initial set-up time (about 2 min of overload time, due to correct repositioning and patient registration), and localization supports did not influence the ergonomics of the mounting tools. Breathing, insufflation, patient repositioning and organ shifting induced a global error that, at the target site (the tumour in the pancreas), was measured in about 20 mm. It is important to notice that the pancreas is a floating anatomical structure; thus, 20 mm can be assumed as an estimation of the worst-case error. In the opinion of the surgeon who used the system, the obtained precision is sufficient to improve orientation and to provide helpful visual assistance during surgical navigation (the surgeon mentally corrected the registration error). Further, the navigation system is valuable for educational purposes: trainees inside the operating room benefit from the additional views provided by the navigation system in the interpretation of laparoscopic images and in the understanding of the phase of the surgical procedure. At the current stage, the system cannot be used for 'blind' guidance during surgical intervention or to implement closed-loop control with operative robots (where high registration precision is required).

Conclusions and Future Work

We have developed the hardware and software architecture of the EndoCAS navigator platform for general CAS applications. We have also evolved a specific application for computer-assisted laparoscopic procedures based on the EndoCAS platform. Preliminary clinical experiences on its use in the OR have been very positive, highlighting several benefits for the surgeon during all phases of surgical management (pre-operative work-up, procedure planning and procedure execution) and also for educational purposes. Actual and future work is focused on the definition of a standard protocol for the acquisition and segmentation of medical datasets (in order to reduce variability in the input data). Deformable object registration techniques (40,41), based on intra-operative medical imaging (laparoscopic or US images) (42,43), constitute one of our actual research areas. The implementation of 'on-the-fly' rigid registration methods based on intra-body anatomical landmarks will be integrated in the system to correct the initial registration error due to the rigid registration procedure based on external fiducial markers. Clinical validation of the system with more fixed structures (such us retroperitoneal organs anchored to the spinal cord) is in the starting phase.

Acknowledgements This work was financed by the Ministero dell'Istruzione dell'Universit`a e della Ricerca (MIUR) and by the Fondazione Cassa di Risparmio di Pisa.

References

1. Faraz A, Payandeh S. *Engineering Approaches to Mechanical and Robotic Design for Minimally Invasive Surgeries (MIS).* Kluwer Academic: Amsterdam, 2000; 1–11.

2. Cuschieri A. Laparoscopic surgery: current status, issues and future developments. *Surgeon J R Coll Surgeons Edinb Ireland* 2005; **3**: 125.

3. Taylor RH, Stoianovici D. Medical robotics in computerintegrated surgery. *IEEE Trans Robotics Autom* 2003; **19**: 765–781.

4. Dario P, Hannaford B, Menciassi A. Smart surgical tools and augmenting devices. *IEEE Trans Robotics Autom* 2003; **19**: 782–792.

5. Peters TM. Image-guided surgery: from X-rays to virtual reality. *Comput Methods Biomech Biomed Eng* 2000; **4**(1): 27–57.

6. Peters TM. Image guidance for surgical procedures. *Phys Med Biol* 2006; **51**: R505–540.

7. DiMaio S, Kapur T, Cleary K, *et al*. Challenges in image-guided therapy system design. *NeuroImage* 2007; **37**: 144–151.

8. Stoianovici D,Whitcomb L, Anderson J, *et al*. Amodular surgical robotic system for image guided percutaneous procedures. *Lect Notes Comput Sci* 1998; **1496**: 404–410; Medical Image Computing and Computer-Assisted Intervention (MICCAI 1998), Cambridge, MA, USA.

9. Burschka D, Corso JJ, Dewan M, *et al*. Navigating inner space: 3D assistance for minimally invasive surgery. *Robotics Auton Syst* 2005; **52**: 5–26.

10. Dario P, Carrozza M, Marcacci M, *et al*. A novelmechatronic tool for computer-assisted arthroscopy. *IEEE Trans Inform Technol Biomed* 2000; **4**(1): 15–29.

11. Focacci F, Piccigallo M, Tonet O, *et al*. Lightweight hand-held robot for laparoscopic surgery. IEEE International Conference on Robotics and Automation (ICRA 2007), Rome, Italy, 10–14 April 2007; 599–604.

12. Medtronic Surgical Navigators: http://www.medtronicnavigation. com/procedures/.

13. Traxtal Percutaneous Surgical Navigator: http://www.traxtal. com.

14. Enquobahrie A, Cheng P, Gary K, *et al*. The image-guided surgery toolkit IGSTK: an open source C++ software toolkit. *J Digital Imaging* 2007; **20**(suppl 1): 21–33.

15. Gary K, Ibanez L, Aylward S, *et al*. IGSTK: an open source software toolkit for image-guided surgery. *Computer* 2006; **39**(4): 46–53.

16. 3DSlicer software: http://www.3DSlicer.org.

17. Julius Software Framework: http://www.julius.caesar.de/index. php/Main Page.

18. Adams R, Bischof L. Seeded region growing. *IEEE Trans Pattern Anal Machine Intell* 1994; **16**: 641–647.

19. FanJ, ZengG, BodyM, *et al*. Seeded region growing: an extensive and comparative study. *Pattern Recogn Lett* 2005; **26**: 1139–1156.

20. Kass M, Witkin A, Terzopoulos D. Snakes: active contour models. *Int J Comput Vision* 1988; **1**: 321–331.

21. He L, Peng Z, Everding B, *et al*. A comparative study of deformable contour methods on medical image segmentation. *Image Vision Comput* 2008; **26**(2): 141–163.

22. Lorensen WE, Cline HE. Marching cubes: a high resolution 3D surface construction algorithm. Proceedings of the 14th Annual Conference on Computer Graphics and Interactive Techniques (SIGGRAPH 87), New York, USA, 1987; 163–169.

23. Montani C, Scateni R, Scopigno R. A modified look-up table for implicit disambiguation of Marching Cubes. *Visual Comput* 1994; **10**(6): 353–355.

24. Ciampalini A, Cignoni P, Montani C, Scopigno R. Multiresolution decimation based on global error. *Visual Comput* 1997; **13**(5): 228–246.

25. OpenSG software: http://www.opensg.org.

26. NDI website: http://www.ndigital.com/.

27. Megali G, Tonet O, Stefanini C, *et al*. A computer-assisted robotic ultrasound-guided biopsy system for video-assisted surgery. *Lect Notes Comput Sci* 2001; **2208**: 343–350; Medical Image Computing and Computer-Assisted Intervention (MICCAI 2001), Utrecht, The Netherlands, 2001.

28. Park F, Martin B. Robot sensor calibration: solving $AX = XB$ on the Euclidean group. *IEEE Trans Robotics Automat* 1994; **10**: 717–721.

29. Maintz JBA, Viergever MA. A survey of medical image registration. *Med Image Anal* 1998; **2**(1): 1–37.

30. Arun KS, Huang TS, Blostein SD. Least-squares fitting of two 3D point sets. *IEEE Trans Pattern Anal Mach Intell* 1987; **9**(5): 698–700.

31. Fitzpatrick JM, West JB, Maurer CRJ. Predicting error in rigidbody point-based registration. *IEEE Trans Med Imaging* **17**: 694–702.

32. Mellor JP. *Enhanced Reality Visualization in a Surgical Environment*. Tech. Rep. AITR-1544. MIT: Cambridge, MA, 1995.

33. Lorensen W, Cline H, Nafis C, *et al*. Enhancing reality in the operating room. Visualization 93 Conference, San Jose, CA, USA, 1993; 410–415.

34. Ferrari V, Megali G, Cappelli C, *et al*. Improving daily clinical practice with 3D patient-specific anatomical models: limits, methodologies and our experience. 6th International Conference on the Management of Healthcare & Medical Technology (HCTM), Scuola Superiore SantAnna, Pisa, Italy, 3–5 October 2007.

35. Yushkevich PA, Piven J, Cody Hazlett H, *et al*. User-guided 3D active contour segmentation of anatomical structures: significantly improved efficiency and reliability. *NeuroImage* 2006; **31**(3): 1116–1128.

36. ITK-SNAP software: http://www.itksnap.org.

37. Zhang Z. A flexible new technique for camera calibration. *IEEE Trans Pattern Anal Mach Intell* 2000; **22**(11): 1330–1334.

38. HALCON software: http://www.mvtec.com.

39. Ayoub J, Cohendy R, Dauzat M, *et al*. Non-invasive quantification of diaphragm kinetics using m-mode sonography. *Can J Anaesth* 1997; **44**: 739–744.

40. Zitova B, Flusser J. Image registration methods: a survey. *Image Vision Comput* 2003; **21**: 977–1000.

41. Hawkes D, Barratt D, Blackall J, *et al*. Tissue deformation and shape models in image-guided interventions: a discussion paper. *Med Image Anal* 2005; **9**(2): 163–175.

42. Szpala S, Wierzbicki M, Guiraudon G, *et al*. Real-time fusion of endoscopic views with dynamic 3D cardiac images: a phantom study. *IEEE Trans Med Imaging* 2005; **24**(9): 1207–1215.

43. Brendela B, Winterb S, Rickc A, *et al*. Bone registration with 3D CT and ultrasound datasets. *Int Congr Ser* 2003; **1256**: 426–432.