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Issues in image-guided therapy

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Medical robotics, Computer Assisted Surgery (CAS), Image-Guided Therapy (IGT) and the like emerged more than 20 years ago and it must be recognized that many advances have been made. Conferences, workshops, have been organized, scientific contributions, position papers and patents have been published, new academic societies have been launched and companies created all over the world to propose methods, devices and systems in the area. Researchers in robotics, computer vision and graphics, electronics, mechanics, biomedical engineers, physicians and surgeons have been involved, thus demonstrating the enthusiasm for this emerging field. Their commitments emphasize the transdisciplinary nature of the efforts to be made. However, the effective dissemination of CAS-IGT systems in medical disciplines remains limited. There are several reasons that may explain this situation, among which the effective demonstration of patient benefits and cost savings, the reluctance of surgeons or therapists to use them and, of course, the technological breakthroughs that are still expected. This series of papers attempts to point out some of them and will also show that many opportunities in computer assisted interventions are open in the near future.

The conjunction of IGT and MIT: the same expectations

With the availability of high resolution medical imaging, in space and time, and the subsequent access to morphological or functional features, the fast developments in image analysis (figure 1) and virtual augmented/mixed reality, and the emergence of microtechnology-based devices, the road was open toward intra-operative image-guided procedures. If the former provides the capability to collect precise and relevant data on the patient disorders, the others offer on one hand, means for objective delineation and quantification of lesions as well as registration, instrument tracking and visualization for multimodal fusion and, on the other hand, the possibility to act in spatially constrained environments. Two major trends have been in fact observed over the two last decades. The first one is related to computer-assisted surgery or image-guided therapy, which can be considered as “technology-driven” and the second one is due to innovations coming from clinicians that are identified under the names of “minimal access therapy” (MAT), “minimally invasive surgery” (MIS) or “minimally intervention therapy” (MIT). They have many aspects in common that have been already stated in the 80’s [1] [2] [3]. In particular, they are aimed at less invasive intervention, reduction of complication risk and of intervention length, less trauma to the patient, lower recovery time with improvements in action accuracy, decreased irradiation for the medical personnel. Even new ways to care the patients were anticipated that could not be undertaken with standard procedure.

Background and scope

The range of image-guided therapies is very large. If the early applications dealt with biopsy, especially needle targeting for brain lesions in stereotactic conditions (figure 2), they quickly addressed the fields of orthopaedics (joint replacement) and more recently cancer treatment (i.e. prostate brachytherapy) and cardiology (such as mitral valve repair) (figures 3 and 4). A global view of the systems developed before 2003 is available in [2]. A more recent survey is provided by J Troccaz [4] where three main periods are sketched: (i) accurate positioning tasks, carried out by a robot using numerical data with main applications in neurosurgery and orthopaedics for simple trajectories and rigid structures (1985–1995); (2) interactive schemes for more complex interventions (endoscopic surgery for instance) dealing with deformable tissues (1990–2005); (3) miniaturized robots (from 2000 and up) capable to perceive, communicate and act inside the human body.

These systems have evolved in their concepts and design according to the attribution and the distribution of the task levels between man and machine and to the on-going technological breakthroughs. In addition, the attractive character of the computer simulation – whose degree of maturity resulted in the emergence of virtual/mixed reality concepts – is related to the possibility of artificially recreating real experimental conditions, to even make cohabit synthetic objects (or conditions, environments) with real objects in the same perceptual space [5]. In fact, such concepts intervene for example in the supervised control of automated or robotized systems for which real-time feedback (haptic rendering, visual rendering) is a prevalent component of the co-operation between the user and the system. Computer-aided therapy (with either passive, synergistic or active guidance) can largely take benefit of virtual/mixed reality like

approaches. In our own views (figure 5), the essential point consists to place (or to merge) the user, namely the expert, his/her knowledge and expertise, at the centre of the system, i.e. of the action, the critical decisional tasks falling onto him whereas the calculative and repetitive tasks come under the responsibilities of the computer. Such an approach relies on the development of a Virtual Environment (VE) devoted to a “patient specific simulation” of the intervention from preoperative data, and in its update according to the intra-operative observations. In the same way as real environment, the range of the virtual environment relates to the pre- intra- and post-operative phases, the observations, decisions and actions carried out during the intervention being able to make it possible to deal with problems which are difficult to solve within only sight of the pre-operative phase, even if the set of data is dense and the time dedicated to the reasoning is long.

First key issues

Performance and benefits assessment: the clinical added-value demonstration

This is perhaps the major question to be answered. If we look at the current market situation, it must be recognized that if a lot of systems have been developed in research laboratories, only a few of them have really reached the clinical settings. In [4], an overview is provided that shows that even the number of the most well-known systems, DaVinci, Aesop is below one thousand over the world in 2008, while others such as Robodoc and Caspar are only approaching a few tens. Another feature, the number of interventions performed using these systems, would be of interest to measure their impact. Thus, although they deal with a large spectrum of clinical applications, computer-assisted systems have still to find their place in practice.

Standards

One requirement pointed out in position papers [6] [7] is the elaboration of performance standards for validation. They call not only for defining average and standard deviation errors in all the sub-processes or components involved in these systems but also providing the observed worst-cases. Workflow methods are recommended for designing surgical/interventional procedures. They emphasize the necessity to have a consensus in setting the requirement specifications as well as gold-standards based on appropriate measurements and evaluation metrics. The option of open source software is also discussed, in particular regarding reliability, maintenance and responsibility.

Technical topics

The above concerns do not mean that all technical problems have been solved. Advanced intra-operative approaches rely on efficient image acquisition/registration, fast and effective image segmentation, high resolution visualization and navigation. If all these issues have received much attention in the last decades, there is however a large space for innovation on many aspects like virtual physiology [8] and functional behaviour control/repair, tracking devices, handling the intra-operative tissue deformations, designing new therapeutic resources, with always the objective to operate in real-time.

Conclusion

If robot-assisted techniques are far to be generalized yet and if minimal invasive methods remain debated due to the occurrence of re-interventions, a large part of interventions are now image-guided. The constant improvements brought by MRI, MDCT, Rot-X, optical imaging, etc. will continue to open new windows on diseases. This trend makes more urgent to have at our disposal new therapeutic resources. It will be shown in the second paper of this series that much remains to be done in this area but also that new windows can be foreseen.

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Figure 1

The advances in medical imaging modalities versus signal-image analysis methods over time

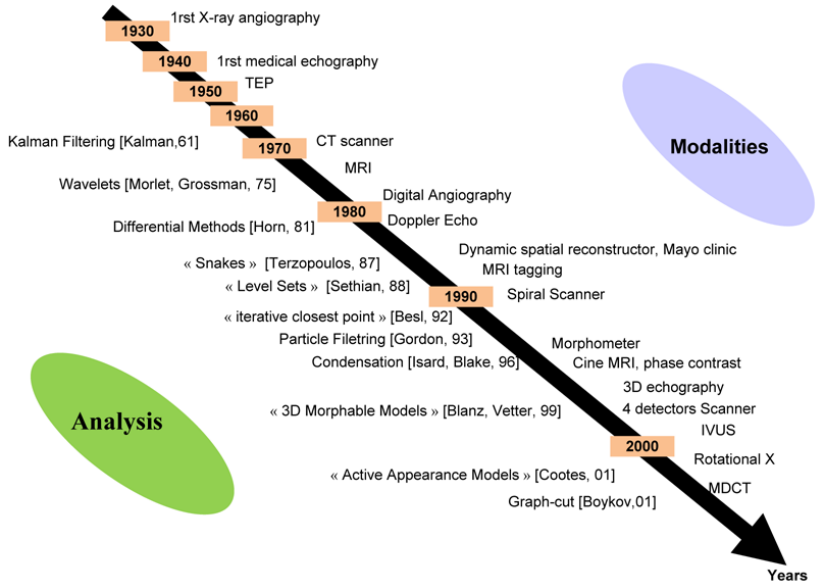


Figure 2

The pioneering robot, IGOR, designed by S Lavallée and P Cinquin, TIMC, in 1989, for brain biopsy (stereotactic frame on the left, robot arm on the right, with X-ray guidance of the needle, middle)



Figure 3

The most popular device, DaVinci, developed by Intuitive Surgical, ©[2009] Intuitive Surgical, Inc.



Figure 4

The LER-VIkY®, TIMC-Endocontrol Medical, France. The first prototype was designed in 2000 and the system has been marketed in Europe in 2007. (Courtesy J Troccaz)



Figure 5

The LTSI views of virtual/real co-operation with priorities on i) analytical exploration (virtual exploratory navigation, description of the patient data) and visualization, ii) patient-specific modelling and simulation of tools/tissues interactions, iii) matching of the different observation phases and iv) real/virtual co-operation with the actualization of each environment (real and virtual) and the development of mixed reality interfaces for the guidance of interventions.

