**A&QT-R 2004 (THETA 14)**
**2004 IEEE-TTTC - International Conference on Automation, Quality and Testing, Robotics**
**May 13 – 15, 2004, Cluj-Napoca, Romania**

# Medical Image-Guidance and Robotics from a Software Perspective

**Mihai Mocanu, Ph.D., MIEEE**

Associate Professor, Department of Software Engineering, University of Craiova, Romania,
5th Lapusului Str., 1100 Craiova, tel/ fax. +40 251 438198, email: mocanu@comp-craiova.ro

Abstract: Although sophisticated software and hardware components are becoming increasingly available, technology for the operating room and interventional suite and the integration of vendor specific software and hardware components remains difficult, and the resulting systems are limited in reuse, flexibility, interoperability, and maintainability. One potential solution to this problem is to develop and test open software architectures as a platform for rapidly integrating new technologies into the operating room. For medical imaging and robotics systems, the development of application testbeds is also critical to move the field forward. These testbeds can also serve to improve the dialog and co-operation between engineers and clinicians.

Keywords: medical robotics, augmented reality, open software architecture

## 1.INTRODUCTION

As part of medical and surgical procedures, there are many situations where precise manipulation of instruments is important. Matching of the information gained from a 3D image (virtual image) with the on-site patient (real image) is generally referred in all research concerning the field of computer-aided surgery (CAS) as *augmented reality*. The purpose of augmented reality is the integration of real and virtual entities to reach a certain goal. In medical applications, this goal is to increase procedure quality and to reduce its time, thus minimizing patient trauma and improving care.

Novel integrated systems aiming this, incorporating tracking, visualization, and robotics, may enable the physician to more accurately target hard-to-reach anatomy as well as target the anatomy directly from the images themselves. Clinical scenarios, technology requirements, co-operation between engineers and clinicians, training needs of health care professionals, and technology integration issues are still problems not easy to overcome.

Of the significant contributions to medical procedures which have been made during the last three decades, many are based on advancements in instrumentation, computer technology, and imaging. Image guidance (IG) has been used in one form or another in various medical procedures since the first applications of ionizing radiation, and, gradually, reviewing patients X-rays, computer assisted tomography (CAT) and/or magnetic resonance imaging (MRI) scans became indispensable to any surgeon.

Medical robotics is today placed to the standpoint that it could “make its move". Still many questions remain as to effectiveness, safety, and cost. Although there are already some commercial companies selling medical robots, the total installed base is extremely small. What it is perceived as a limiting factor today is a robot ability to react and our capacity to rely on them in sometimes complex environments. In particular, ***robust** vision* (as the most versatile sense of perception, required to aid the control of motion of an autonomous robot arm) is a key bottleneck to the development of medical robotic procedures. Therefore, new generations of robots have specialized mechanical designs and use sensing technologies, video images but also force sensations, aimed to maximize dexterity under access constraints. Novel integrated systems incorporating computer visualization and robotics also proved their value in enabling the physician to more accurately target hard-to-reach anatomy directly from the images themselves.

## 2.INTRA-OPERATIVE IMAGE GUIDANCE

Intra-operative image guidance is a natural step forward for IG, determined by the surgeon’s important need to see some procedures as they are performed in real time, or to simulate, plan and discuss them prior to any intervention.

The increasing demand for refinement of imaging and image representation for interventions and surgery requires methods for data acquisition, processing and display and a thorough understanding of the process of imaging and its applications to therapy. *Medical visualization* requires computerized image processing methods (segmentation, registration, display) and image integration techniques to replace the mental process of generating 3D representation of the patient’s anatomy. As part of today standard procedures, there are many clinical situations where reduced trauma, enhanced vision modalities for the physician and precise manipulation of instruments, are among the most important factors for success. Radiological, ultrasonic, and magnetic resonance imaging are the usual techniques employed to enhance vision in intra-operative procedures [5][9][10]. The clinical emergence of new technologies, providing the surgeon image visualization and analysis capabilities during 'real time' surgery, and all at once of new problems, has been reported since more than a decade ago by neurosurgeons. It has then been proven that computer generated data can be transposed accurately on the `real' physical world or can be used to drive instruments such as microscopes, lasers, etc., leading to automation of neurosurgical procedures [14]. Other medical fields have adopted and adapted similar techniques. Improved intra-operative image guidance, by fluoroscopy or ultrasound imaging or other modalities, proved to be effective to reduce the intrinsic invasiveness of surgery. The continuous and marked increase in interest can be largely attributed to the development of *minimally invasive procedures*, conditioned by progresses in technology, increased computer power and imaging algorithmics [12].

Visualization during surgery cannot be complete (the surgeon cannot see directly beyond the uncovered surfaces). There are even greater restrictions in minimally invasive surgery. Visibility via small incisions with narrowing sizes increases the need for intraoperative image guidance. During minimally invasive procedures, the surgeon does not have a direct view of anatomic structures, and must rely instead on indirect views provided by imaging modalities such as X-ray fluoroscopes. This is more challenging and requires the physician to be highly experienced. Successful targeting of an anatomic structure is dependent on the surgeon’s skill, especially if the target is small. But in spite of this serious problem encountered - a dramatic reduction in the surgeon's visual ability and dexterity, in contrast to open procedures -, minimally invasive procedures are rapidly expanding, due to the substantially reduced trauma for the patient. Moreover, several surgical specialties have already been transformed by minimally invasive surgery [7]. A pervasive transformation is towards making them "radiological interventions", highly dependent on new technology - like portable ultrasonic and fluoroscopy units (C-Arms), ever-present in modern operations.

## 3.MEDICAL ROBOTICS

Medical robotics is a relatively young field, it was established in the sixties when in the fields of orthopaedics and neurology was a high interest to develop active prostheses or orthotic devices to replace limbs or to support paralyzed segments of extremities. The first recorded medical application of a robot occurred in 1985 [6]. In this case, the robot was a simple positioning device to orient a needle for biopsy of the brain.

Shortly thereafter, research groups in Europe, Asia and the U.S. began investigating medical applications of robotics [3]. In Europe, a group at Imperial College in London under the direction of Davies began developing a robot for prostate applications [4], and at Grenoble University Hospital in France, Benabid, Lavallee, and colleagues started work on neurosurgical applications such as biopsy [1]. In Asia, Dohi at Tokyo University developed a prototype of a CT-guided needle insertion manipulator [13]. In the U.S., Taylor and associates at IBM began developing the system later known as ROBODOC [11].

From the standpoint of mechanics and control, robotics research has already advanced to the point that it could move into the "real" world, which includes the very sensitive field of medical robotics. More specific here, given a sufficiently structured environment, today's robots can perform complex tasks with astonishing precision and speed - robots were reported to work with high precision, sometimes better than the human hand.

One of the key modalities to address factors like *precision*, *stability*, and *dexterity*, in CAS, is through the integration of other new technologies and tools, like computer-controlled robots that, on one hand, allow the surgeon to work remotely inside the patient's body without making large incisions, and on the other hand, can "register" themselves in a precise and stable manner to the other devices in the operating room. Most methods proposed require time-consuming pre-operative registration procedures between robot, imaging system and the patient's anatomy, but modern approaches to address these problems include computer assisted procedures or robotic systems to assist.

## 4.SOFTWARE ARCHITECTURES AND DESIGN

For medical image-guidance and robotics to evolve as a mature field of research and development, and for the cost and difficulty of developing prototype systems to decrease, the establishment of unifying system architectures can be an enabling step.

An image-guided surgery system typically provides a method for registration of pre-operative images to the physical space of the patient, a user interface that display images and the position of instruments, and a high-performance, integrated hardware/software system. Key software issues addressed here included *portability*, platform *independence*, and parallel execution *speed* usually achieved by pipelining.

In a medical robotics working environment, possibly including an appropriate real-time operating system, the systems architecture should emphasize *modularity*. This was first noted by Taylor in the design of the Steady-Hand robot, which emphasizes modularity in mechanical design, control system electronics, and software. Another important issue for such a system geared to the medical environment would be *robustness* with respect to the software employed. Last, but not least, *openess* (including open-source) in software should be at least considered. Many researchers developing medical robotics systems today base their software development on commercially available but closed (“black-box”) software packages that may not be suitable for the surgical environment. However, the low cost and widespread availability of these software packages makes their use attractive and there are steps that can be taken (such as watchdog timers, backup systems, and error recovery procedures) to make these systems more reliable.

Another issue in software architectures underlying hardware systems is also to provide *flexibility* to the applications in the interventional environment. With the increasing popularity of image-guided interventions, robotic systems are also required to work within the constraints of various imaging modalities such as CT and MRI. While these systems are for the most part still under the direct control of the physician, in the future they will be increasingly linked to these imaging modalities.

Main questions that arise in the development of all medical robotics systems also concern the user interface. What is a suitable user interface for a medical robot? Should the robot be given a commanded path or volume and then autonomously carry out the task? Is a joystick or pushbutton interface appropriate? Or would the physician rather manipulate the tool directly with the assistance of the robot? Is force feedback required for a high fidelity user interface? These are all questions that require further investigation by the medical robotics community. The answer certainly will vary depending on the medical task for which the robot is designed. It seems that medical robots will at least initially be more accepted by physicians if they feel that are still in control of the entire procedure.

Software architecture specifications for the integration of imaging, localization, and robotic instrumentation are rarely available, current surgical navigation systems usually employ proprietary software interfaces between fixed instrument types. Since usual developments are based on multiple co-operations, defining a systematic software development process (SDP) is vital. This should include software development based on formal specifications, advanced methods for software design (i.e. UML), rapid application development in a high-level object-oriented language (e.g. C++), and the use of documentation tools (such as Doxygen) and source code control (CVS, SourceSafe). A generic SDP must be defined so that new researchers can build on existing code.

*Layering* is also a possibility to investigate, especially for large software applications. At the lowest level, such system architecture may include proprietary, vendor-specific software levels for individual hardware components such as a motion control card and watchdog timer. On top of this level, a higher-level application programming interface (API) must be built. At the highest level we can place the specific complete application, or a simple user interface, together with customized, reusable libraries.

Some examples of such C/C++ based libraries, largely in use, placed at different levels in our model of development, include the Motion Engineering Incorporated (MEI) DSP-Series Motion Control Library, the Matrox Imaging Library (MIL), the Visualization ToolKit (VTK) from Kitware or the Insight Toolkit (ITK) still in development by the Insight Consortium. When developing a specific library, i.e for future robotics software systems, attention should be paid to portability – an example here is that at least the core part of the library should not make use of proprietary classes (e.g. Microsoft Foundation

Classes), flexibility and ease of use (i.e. base all functions on engineering units such as millimeters), ease of progress towards a wide range of applications, an efficient and simple user interface for testbeds, and support for calibration and use in clinical studies [2]

## 5. EXAMPLES

### 5.1.*IGBiopsy*

IGBiopsy is a system developed at Georgetown University, USA, and presented in much more detail in [2], incorporating magnetic tracking for image guidance during minimally invasive abdominal interventions. We shall summarize here only the object oriented design of the system and review the SDP.

The object-oriented design for the system is based on a formal and iterative process of decomposing requirements by objects rather than by functions through multiple design cycles. Generic steps performed are:

- Identification of main objects that describe entities and processes in the environment.
- Definition of views that will be used to present those objects to users.
- Determination of interactions between entity and process objects for specific tasks.

This design process was applied from the initial development of the system. This led to a design decision to base the system on software libraries currently in widespread use: OpenGL, Visualization Toolkit (VTK), Fast Light Tool Kit (FLTK), in which:

- The “basement” of the system is VTK-FLTK (-OpenGL) –based.
- At the intermediate level therea are generic elements supported in an abstract manner in the system.
- Concrete elements have their role in “transforming” the views, in “selecting” a view or working with specialized views, or in getting probe/catheter data from the tracker.

### 5.2.*Fluoroscopy Servoing*

*Intra-operative fluoroscopy* is a valuable tool for visualizing underlying patient and surgical tool positions in radiology procedures. *Visual servo control* is a novel strategy based on the use of visual information in a feedback loop for the position and motion control of autonomous robot manipulators evolving in unstructured environments. The combination of the two in the area of medical robotics is commonly referred as *fluoroscopy servoing*. Although distinct, the topic of visual servo control extends over many fields of study, mainly related to robotics and computer vision. Different techniques inside this area involve coordinate transformations, velocity representation, but also geometric descriptions and transformations of the image formation process.

Any effort to apply visual servo control in medical procedures must be based on well-suited methods for real-time implementation. In particular, fast execution and resources (processing) redundancy employing parallelism may enable simplified tracking and allow handling of temporary loss of individual features.

A simple and direct technique and software system based on the principles previously exposed, to perform targeting under continuous imaging has been described by us in [8]. No stereotactic frame and no prior calibration of the instruments is required. Three-dimensional targeting is achieved by performing the alignment in a single view acquired at an approximate A/P C-Arm orientation. The percutaneous access implementation of this method provides automated alignment of the needle towards a surgeon specified target. The surgeon using side-view fluoroscopic feedback could then control needle insertion manually. The absence of mandatory pre-operative register, or need to use bi-planar X-ray systems or calibrate the system prior to use was an immediate advantage foreseen.

## 6.CONCLUSIONS

Image-guided surgery is increasingly employed as it can considerably reduce trauma for the patient. Robotic systems may also provide this by their increased precision in performing surgical interventions. They may be integrated with IG systems for targeting purposes. The integration of the software parts of such components, similar to those described in this paper, may lead to the development of novel interventional techniques.

The lifecycle of such software systems usually includes a short initial development phase, a longer phase of product support and refinement, and extensive testing from the customer (physician) perspective. A formal software development and change control process is also needed to ensure reliable and usable systems.

## 7.REFERENCES

[1]Benabid, A. L., P. Cinquin, et al. (1987). *Computer-driven robot for stereotactic surgery connected to CT scan and magnetic resonance imaging.* Appl Neurophysiol **50**(1-6): 153-4

[2]Cleary K., M.Mocanu, et al. (2002). *Software Architecture for Robotically Assisted and Image-Guided Minimally Invasive Interventions*, CARS 2002, Springer, pp.218-223

[3]Davies, B. (2000). *A review of robotics in surgery*, Proc Inst Mech Eng. **214**: 129-140

[4]Davies, B. L., R. D. Hibberd, et al. (1991). *A surgeon robot for prostatectomies*. Fifth International Conference on Advanced Robotics (ICAR '91), IEEE

[5]Jolesz, F. A., A. Nabavi, et al. (2001). *Integration of interventional MRI with computer-assisted surgery*, Journal of Magnetic Resonance Imaging **13**(1): 69-77

[6]Kwoh, Y. S., J. Hou, et al. (1988). *A robot with improved absolute positioning accuracy for CT guided stereotactic brain surgery*, IEEE Trans.on Biomedical Eng. **35**(2): 153-160.

[7]Langlotz, F. and L. P. Nolte (1999). *Image-guided spine surgery*, Minimally Invasive Therapy & Allied Technologies **8**(5): 291-296

[8]Mocanu M., K. Cleary et al. (2003). *Fluoroscopy Servoing using translation Rotation Decoupling in an A/P View*, Proc.SPIE, vol.5029, pp.161-165

[9]Murphy, M. J., J. R. Adler, Jr., et al. (2000). *Image-guided radiosurgery for the spine and pancreas*, Comput Aided Surg **5**(4): 278-88

[10]Sato, Y., M. Nakamoto, et al. (1998). *Image guidance of breast cancer surgery using 3-D ultrasound images and augmented reality vis.*. IEEE Tr. on Med.Imaging **17**(5): 681-93

[11]Taylor, R.H., B.D. Mittelstadt, et al. (1994). *An image-directed robotic system for precise orthopaedic surgery*. IEEE Trans. on Robotics and Automation **10**(3): 261-273.

[12]Viergever, M. A. (1998). *Image guidance of therapy*, IEEE Transactions on Medical Imaging **17**(5): 669-671

[13]Yamauchi, Y., T. Dohi, et al. (1993). *A needle insertion manipulator for X-ray CT image-guided neurosurgery*, Proc LST **5**: 814-821

[14]Zamorano, L., C. Chavantes, et al. (1990). *Three-dimensional image-guided stereotactic resection of intracranial lesions.* Proc.SPIE, Los Angeles, CA, USA