Flexible architecture and modularity requirements for image guided cardiovascular surgeries

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Abstract

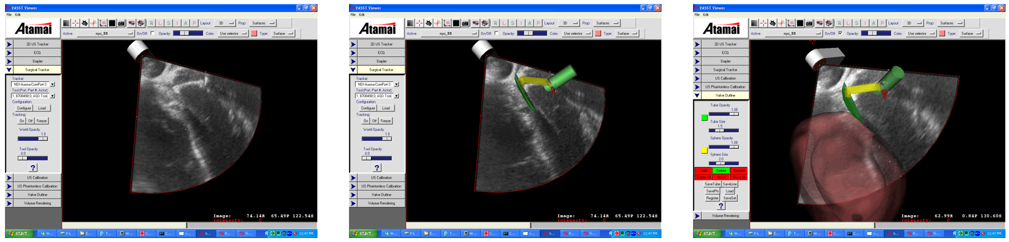
Research and development of image guided surgery techniques requires software that provides a high degree of flexibility, with easy access to reliable functionality for common tasks. The goal of this paper is to highlight this claim in the context of image guided cardiac surgery applications. Cardiac surgery traditionally involves very invasive surgical procedures. Minimally invasive surgical techniques can greatly reduce the invasiveness of these procedures, thus reducing patient trauma. Implementing new image guidance systems for cardiac surgery is a complex process, requiring the integration of a wide variety of physical and software systems, involving both research and clinical personnel. Modular software design is essential to accommodate this complexity. Furthermore, software architecture must be highly flexible in order to facilitate both the adaptability necessary in research, and the tested reliability needed for clinical applications. Over the past decade, our laboratory has created a comprehensive system for research and development, testing and implementation of new surgical guidance techniques in the operating room. This paper provides an overview of our approach to the development and implementation of image guided therapy software for cardiovascular surgeries, ranging from the simple (needle guidance for central line access) to highly complex and experimental (intracardiac beating heart mitral valve repair/replacement).

Contents

1 Introduction

In many forms of surgery, the target tissues are quite small, and gaining direct access to these tissues requires highly invasive interventions. Many cardiac surgery procedures fall into this category; the combination of mid-sternotomy and cardiopulmonary bypass often prove more traumatic to the patient than the actual therapy performed in or on the heart. For such procedures, minimally invasive access via mini-thoracotomy or trocars inserted between the ribs and performing therapies on the beating heart can greatly reduce patient trauma. Along with the challenge of redesigning surgical tools for limited access, surgeons are also faced with the challenge of limited, or no, direct visual access to targeted tissues, thus requiring the introduction of navigation and visualization systems for image guided therapy (IGT).
A general paradigm [3] for IGT is shown in Figure 1. High resolution preoperative images are acquired, and registered to the patient at the start of the surgery. Surgical tools are tracked, and integrated into the visualization environment. This information is presented to the surgeon using overhead monitors or other devices such as head-mounted displays (HMDs), as a means of providing the guidance information no longer available to direct vision. This general paradigm can be adapted in many ways, depending on the specific application, and we have developed several such applications related to cardiovascular procedures. Our approach is to adapt imaging technologies such as ultrasound (US) and fluoroscopy already present in most operating theaters to ensure our IGT techniques are available to a wide community at minimal cost. Three projects are briefly described to highlight the range of demands placed on the IGT software platform.

Figure 1: A generalized image guided therapy paradigm.



(a) TEE data alone (b) TEE plus VR tool (c) TEE plus models

Figure 2: Comparison of TEE guidance alone with TEE plus virtual tools and models.

2 Methods

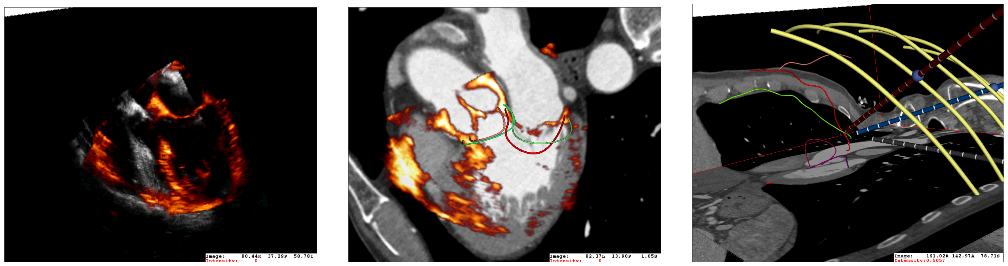
In order to properly appreciate the importance of modular design in IGT, the variety and complexity of the physical systems to be integrated must be considered.

2.1 Cardiovascular IGT

Intracardiac surgeries

As described by Linte et al [7], our laboratory has developed a comprehensive system for performing off-pump intracardiac surgeries for mitral valve replacement and atrial septal defect repairs. This system uses the Guiraudon Universal Cardiac Introducer [6] as a double lock system for safely introducing a variety of surgical tools into the beating heart. One of the greatest challenges with this surgical technique is the lack of direct visual information for guidance. The surgeon must rely on US image data provided by transesophageal echo (TEE) for real time visualization. However, US alone provides very limited information, making it difficult to visualize both tools and surgical targets simultaneously, even with 3D TEE technology. The surgical tools themselves often "shadow" critical anatomy distal to the US transducer, making it impossible to identify critical landmarks. Further, the cognitive skills required for translating US data on a monitor to real anatomy and tools can be quite demanding.

To overcome these difficulties, we employ "virtual reality-enhanced US," in which the real time US data are presented in a full 3D context with virtual representations of all tools as well as preoperative dynamic image volumes, patient specific geometric models of cardiac anatomy and surgical targets (Figure 2). This is achieved by integrating magnetic tracking system (MTS) technology into the TEE transducer and surgical tools in order to place TEE image data (and hence the real-time patient anatomy) in the same 3D coordinate frame as 3D representations of the surgical tools. Virtual reality (VR) representations of the TEE probe (Figure 2a) can be combined with VR representations of surgical tools (Figure 2b) as well as preoperative data or derived models (Figure 2c). With a sufficiently modular software platform, a wide variety of IGT techniques can be easily evaluated, such as different visualization techniques (stereo HMDs versus orthogonal views), wire frame versus semi-transparent elements, different methods for registering preoperative data, and methods for tracking and displaying surgical targets.



(a) TEE data overlay (b) TEE registered to CT (c) Planner module

Figure 3: Perioperative heart shift: a) overlay of TEE data showing initial heart location (gray) with post chest insufflation (hot metal); b) overlay of initial TEE data with preoperative CT data; c) all data loaded in a peri-operative planner, including original and shifted coronary artery locations (red and green splines).

Measuring perioperative heart shift

Unlike the intracardiac surgery project which is at the phantom and animal studies stage, our "heart shift" project revolves around a complex clinical procedure. This project involves collecting data during the perioperative stage of off-pump, minimally invasive robotic coronary artery bypass (MIRCAB) surgery. Our goal is to quantify and statistically analyze the manner in which the human heart shifts in the closed chest due to perioperative interventions such as collapsing a lung and insufflating the chest cavity. This information is of significant value to cardiac surgeons as they select optimal port locations for the robotic arms used in MIRCAB. Currently, cardiac surgeons plan the port locations based on preoperative CT data acquired several days before the surgery. Consequently, any perioperative change in heart location relative to the ribcage is not accounted for, which can lead to the selection of sub-optimal port locations. By measuring this heart shift immediately prior to inserting the robotic arm trocars, we are able to display this shift to the surgeon, either via computer display or by overlaying the shift pattern on the patients chest using an augmented reality technique [8].

As with intracardiac IGT, we make use of standard imaging technology: preoperative CT data and intraoperative TEE imaging. Much the same techniques can be used as were described for intracardiac IGT [1]; MTS systems are used to track the TEE transducer, and anatomical features are used to register preoperative CT data with perioperative ultrasound images (see Figure 3). In this manner, we are able to define a range of pertinent anatomy (coronary ostia, mitral valve annulus, ventricular wall, apex) in both preoperative CT and at the various perioperative stages using the tracked TEE. We map the heart shift by co-registering these datasets, thus improving the selection of port locations for the robotic arms.

While the algorithms, systems and techniques used in this project are quite similar to the intracardiac project, there are significant challenges in adapting these techniques and software into the OR workflow of a highly complex clinical procedure, as will be discussed in section 3.1.

Central line access

A third and final example of cardiovascular IGT we are developing is needle guidance for central line insertion. This procedure involves placing a large cannulated needle into the internal jugular vein. The procedure is a delicate one largely due to the close proximity of the carotid artery and the risk of pneumothoraces (lung puncture). Our approach is once again to use tracking technology to monitor both the needle and US transducer. Virtual models of the US and needle are visualized, along with a virtual representation of the needle trajectory in order to provide the anesthetist with a full 3D context for the procedure (another example of

(a) Cannulated needle with sensor (b) VR enhanced guidance

Figure 4: Central line access: a) magnetically tracked needle and syringe; b) VR enhanced US guidance platform with four-pane view.

VR-enhanced US). This IGT application is relatively easy to implement since it is a simple adaptation of existing clinical technique and practice, and the IGT framework has already been developed and tested for spine and peripheral nerve block applications [2, 9]. Our primary goals are to use the VR-enhanced US to improve both procedure safety and time required for the procedure (see Figure 4).

Once again, this project builds on the algorithms, systems and software developed in other projects. As with the "heart shift" project, this work will soon be employed in a clinical setting. In this case however, the IGT platform will be actively used for procedure guidance, while the heart shift project involves only the collection of new clinical data. This fact in turn has significant implications on our software requirements, as will be discussed in section 3.1.

2.2 Systems integration

A general paradigm for all our cardiac IGT projects is shown in Figure 5. As was mentioned in Section 2.1, numerous physical systems are employed in the various cardiovascular IGT projects. Moreover, many systems can be implemented with a variety of vendors and devices, the most obvious being tracking systems (optical, magnetic, and image-based). Several other components, such as ECG monitoring equipment, video capture devices, and visualization technologies (stereo monitors, HMDs, etc) also come in many flavors, and a variety of vendors. Given this variety, it is essential, especially in the preliminary stages of project development, that our software be highly modular to ensure device independence as we assess optimal systems and algorithms.

2.3 Software platform: AtamaiViewer

Since many of the components required for IGT systems are similar (visualization strategies, tracking technologies, etc), it is obviously advantageous to re-use software wherever possible. Currently, we use a software platform called the 'AtamaiViewer' [5]. This platform uses a modular structure which makes it possible to quickly and easily add new plug-in modules, building on commonly used existing utilities (see Figure 6). It uses an open source code management, with CVS and Doxygen. The Visualization Toolkit (VTK) is used as a framework for image rendering. The AtamaiViewer uses Python as a VTK scripting language, with robust visualization and rendering capabilities (Figure 7).

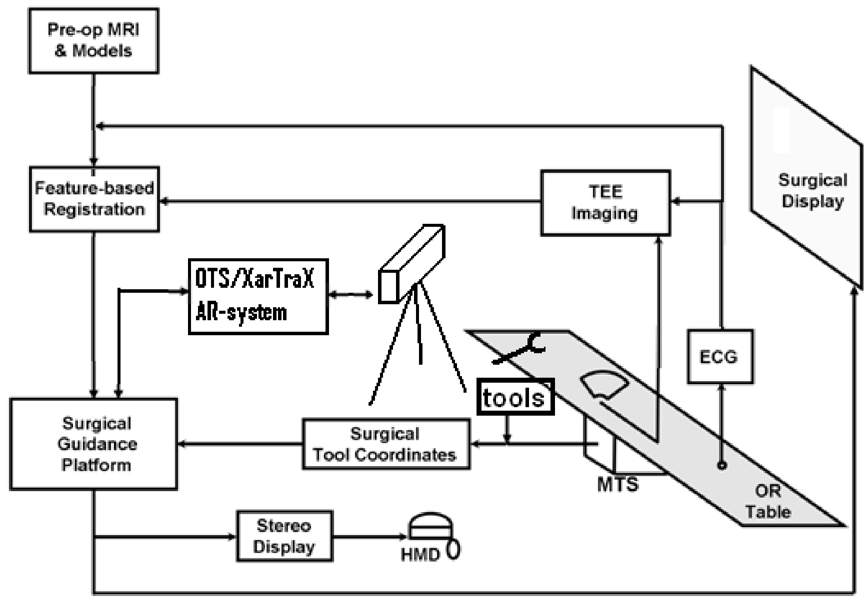


Figure 5: The cardiac IGT paradigm consists of multiple systems, making modular software design essential.

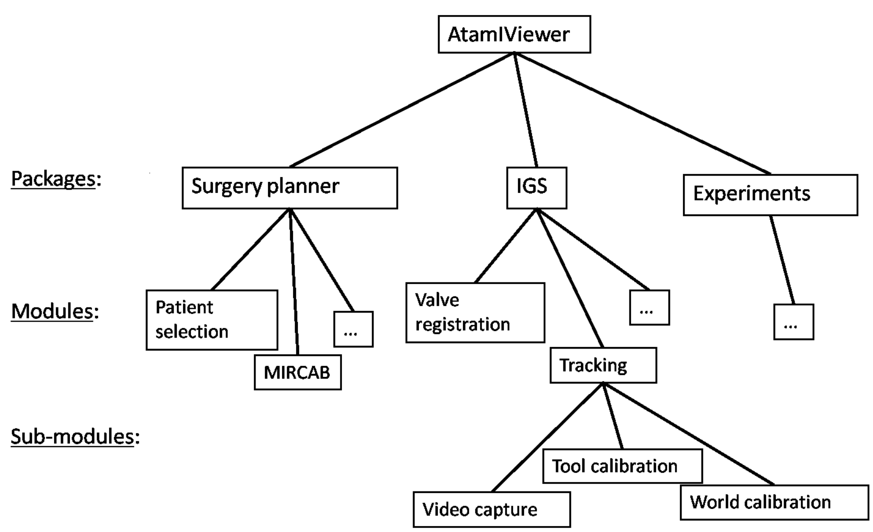


Figure 6: The AtamaiViewer: modular design and sample modules.

3 Discussion

When it comes to IGT software development, there is a significant tension between the demands of highly experimental applications such as intracardiac surgery and patient-ready applications such as central line insertions. The former requires the ability to quickly implement a wide variety of applications such as registration algorithms, tracking and visualization techniques. The latter, on the other hand, requires a clear and precise workflow layout, with little or no immediate support required by software support staff. Patient-ready software must be thoroughly tested to ensure reliability and comprehensive coverage of all contingencies.

3.1 Flexible architecture: applications

For all that we employ similar technology (MTS, calibrated US, etc) in our IGT projects, the research dynamic varies greatly. The intracardiac project is highly experimental, with most experiments performed either in a laboratory setting or in acute animal studies. Since it is in the early stages of development, software goes through substantial modification in relatively short time intervals. For example, several different visualization methods need to be evaluated (immersive 3D, 4 pane views, volume rendering, etc). Experiments and animal studies are flexible enough to allow for unforeseen complications that are inevitable in preliminary research. In contrast to this, the heart shift project involves data collection in a crowded, complex clinical surgery. This application and environment places a different set of demands on our software; we are required to work within an existing and carefully defined OR workflow. Our data acquisition work must conform to existing timelines and schedules, with no room for on-the-fly corrections or modifications. Finally, the central line access project must not only integrate within existing OR workflows, it must also pass thorough testing, since it will be used for actual guidance of the intervention. Modular software structure facilitates the process of creating stand-alone applications, derived from the main IGT software platform. Currently, we are planning to migrate our clinical applications to the Image Guided Surgery Toolkit (IGSTK) [4], given the central importance of patient safety in clinical applications; the deterministic structure and logging capabilities of IGSTK make it well suited for such tasks.

3.2 Flexible architecture: users

Beyond issues of modularity, a flexible architecture is also of vital importance for another facet of our research environment. In most cases, new projects are primarily developed by graduate students who may or may not have experience in computer programming. It is highly advantageous if preliminary software development can be done in high-level languages like Python, since non-programmers can quickly develop the skills necessary to implement new algorithms (for registration, visualization, etc). As a scripting language, Python also has the advantage of eliminating the need for constantly recompiling code. As a software application evolves and becomes more stable, it may be appropriate to convert it from Python to a faster, compiled language such as C++, for the sake of computational efficiency.

4 Conclusions

Three examples of cardiac IGT projects have been summarized. From these examples, it is possible to glean valuable insight into the requirements for IGT software architecture. The first and most obvious is

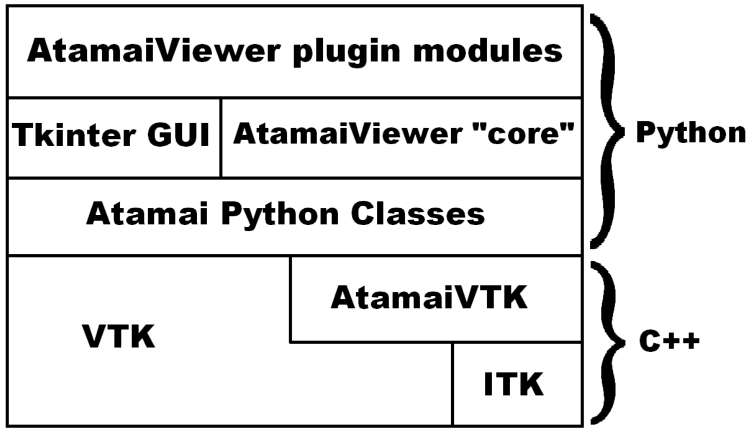


Figure 7: The AtamaiViewer architecture: Python scripts built on C++ (VTK). Figure adapted from [5].

the importance of modular design. Beyond this, a flexible architecture can greatly facilitate long term software development. In the early stages of an IGT research project many strategies and algorithms must be evaluated. However, as a project progresses toward clinical application systems must be optimized and comprehensive testing must be completed. A software architecture capable of managing this progression must be flexible enough to allow easy and rapid development of many prototype applications, but also be capable of generating "spin-off" versions for clinical use by end-users unfamiliar with software design.

Ideally, the transition from research- to clinically-oriented design and development should be seamless. Currently, platforms such as the AtamaiViewer are well suited to the demands of research-oriented projects, while platforms such as IGSTK are best suited for clinical applications. As IGT toolkits and platforms evolve, it is imperative that both clinical and research needs be addressed.

Acknowledgments

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