Planning, Simulation, and Augmented Reality for Robotic Cardiac Procedures: the STARS System of the ChIR Team

Ève Coste-Manière, Louaï Adhami, Fabien Mourgues, and Alain Carpentier

This paper presents STARS (Simulation and Transfer Architecture for Robotic Surgery), a versatile system that aims at enhancing minimally invasive robotic surgery through patient-dependent optimized planning, realistic simulation, safe supervision, and augmented reality. The underlying architecture of the proposed approach is presented, then each component is detailed. An experimental validation is conducted on a dog for a coronary bypass intervention using the Da Vinci™ surgical system focusing on planing, registration, and augmented reality trials.

1 Motivations and Approach

Mini Invasive Surgery (MIS) is defined as a surgery that causes minimal injury to the patient, yet achieves the required surgical goal. In this type of surgery, small incisions are performed on the patient, by which specialized surgical instruments and a videoscope are introduced. Moreover, the limits of minimally invasive techniques are being constantly outdated, especially with the introduction of robots, which remedy the lost precision and dexterity. Nevertheless, using robotic MIS instruments remains unnatural even to the most experienced surgeon, thus rising questionable doubts about whether their potential is being fully exploited. In particular, challenging issues are the placement of the incision points that yields a configuration which enables satisfactory access and adroitness, the positioning of the robot in a clutter operating theater, and the safe and accurate execution of the intervention using the above stated instruments. The difficulty behind the latter problems stems from the large number of factors that influence the ultimate outcome of patient benefit, in which the traditional approach of relying on circumstantial evidence no longer delivers reliable solutions. As a consequence, appropriate preparedness and assistance should be sought using new methods and solutions. The bulk of the work performed in the ChIR Medical Robotics team at INRIA Sophia Antipolis is to seek and propose solutions to preparedness and assistance.

The original motivation for this work came from a medical exposure during the world's first robotically assisted totally endoscopic cardiac intervention at the Hôpital Broussais in Paris, by Pr. Alain Carpentier, Didier Loulmet and the cardiac team using the Da Vinci™ robot in May 1998. Present at the intervention, the INRIA robotics team identified with the surgeons a number of critical steps that would be better handled through computer integrated approach. These included better preoperative planning through mathematical optimization, simulation and enhanced execution through augmented reality. Soon, it became clear that such an approach can only be performed in a safe and integrated environment by a multidisciplinary team composed of surgeons, radiologists and robotics scientists.[5]

In fact, endoscopic cardiac gestures are particularly difficult because of the required precision and the restrained working space. This accuracy is brought by (for instance) the Da Vinci™ system, in which motion tremors can be filtered out and movements decoupled in magnitude. However, the access through intercostal spaces still restrains the movements of the instruments (limited angulation and rigid ports), leading to a difficult port placement if only three incisions (two for the instruments and one for the videoscope) are to be used. Moreover, the closeness of the access ports and the large size of the robotic

From the ChIR Medical Robotics team, INRIA Sophia Antipolis (www.inria.fr/chir). E-mail: eve.coste-maniere@sophia.inria.fr.
Address reprint requests to Hôpital Européen Georges Pompidou, Service de Chirurgie Cardiaque, 20, rue Leblanc, France.

1043-0679/03/1502-0006$30.00/0
doi:2003.xxxxx

system present a significant potential for collisions during the intervention, either between the manipulator arms or with the patient's shoulder or hip.[9]

The main reason behind the above described problems was that the complexity of the settings, combined with the novelty of the methods used, prevented an intuitive optimization of the operating conditions. As a consequence, STARS (Simulation and Transfer Architecture for Robotic Surgery), a computerized system is developped.

Paper Outline

The approach behind STARS is summarized in figure 1 and table 1. Beyond cardiac surgery, the system has proven to be generic and to allow to alleviate the use of surgical robots in other clinical fields (urology, digestive, neuro surgery, etc.).

The paper is organized around the description of each of the above steps. An experimental validation performed on a dog demonstrates the added value of the approach. Finally, trends for the future are drawn.

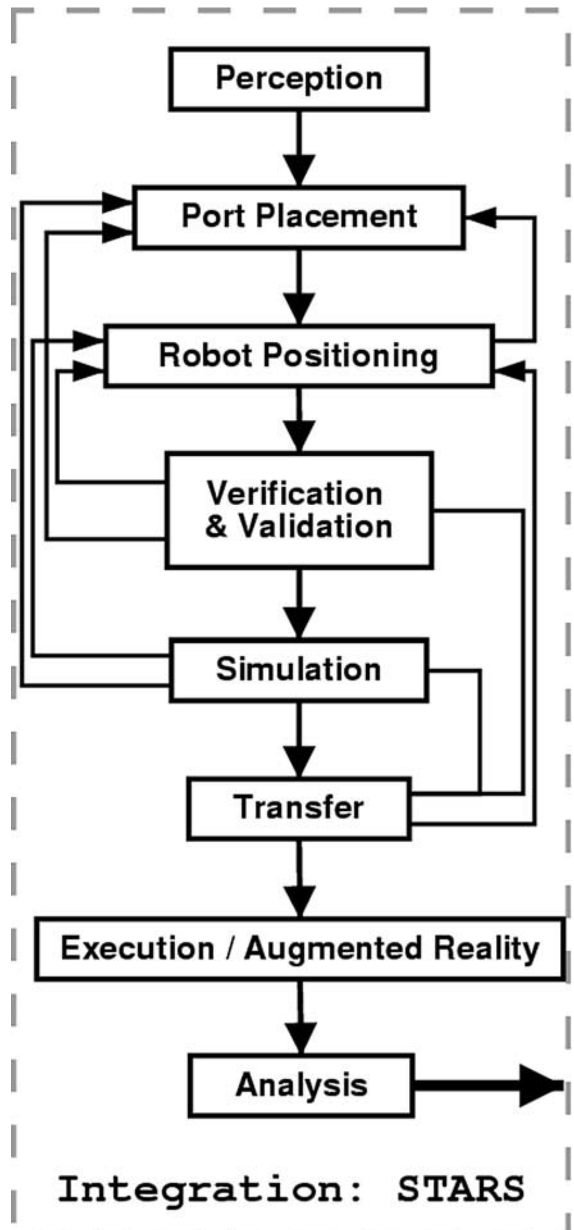

Figure 1. General CIS approach, a more detailed description is found in.[2]

2 Perception

A preliminary step to any form of processing is to acquire relevant and usable data. In the case of computer integrated robotic surgery, three sources of information have to be combined. Namely, data about the patient that describes the overall anatomy and gives clear pathologic indications, a model of the robot that can be used to accurately predict its behavior and interaction with its surrounding, and finally a model of the surgical setup or the operating theater that serves to consolidate preoperative planning and simulation with intraoperative execution.

2.1 Patient Model

Patient data are mainly obtained from preoperative radiological imaging. An interactive 3-D segmentation system is used to delineate semantically significant entities for further analysis; eg, ribs must be isolated and numbered for the planning phase described in section 3. Moreover, 3D reconstruction is used to transform volumetric data into surface data that are easier to visualize and manipulate. Examples of manual and automatic segmentation are shown in figure 2. Under-sampling and triangulation of the segmented data are necessary to enable advanced manipulations such as deformations or active constraints (see section 6).

2.2 Robot Model

The kinematics and shape of the robot are inputted using a simple modeling syntax. Standard DH

Table 1.

Perception: Gather information about the patient, the robot, and the environment.
Port Placement: Determine the best incision sites (ports) based on intervention requirements, patient anatomy, and tools specs.
Robot Positioning: Determine the best relative position of the robot, the patient, and the operating theater.
Verification and Validation: Automatically validate planning results under more realistic operating conditions and verify the operating protocol and the corresponding robot logic flow.
Simulation: Rehearse the intervention using patient and robot data in simulated operating conditions.
Transfer: Transfer the results to the operating room through proper registration and positioning.
Execution/Augmented Reality: Execute planned results with visual/computational assistance, monitor and predict possible complications.
Analysis: Store the settings and history of the intervention for archiving and subsequent analysis.
Integration: All the components of this architecture are integrated into a modular single-interfaced system: STARS

coordinates are used for kinematic description, whereas the physical envelope of the robot is approximated with basic geometric primitives, namely, regular parallelepipeds, cylinders and spheres. This format accepts any general open-chain multi-armed robotic systems; close chains can also be used but are more difficult to model. The main originality of the format is its ability to model special surgical robotic features such as an endoscopic arm and a variety of surgical tools. A camera can be added anywhere on the robotic chain, and can take different attributes such as a projection matrix. Likewise, different types of tools can be added to model interactions such as cutting tissue.

2.3 Environment Model

The environment is represented using a geometric model of the operating theater and approximations of the surrounding material. An extra realism can be added through texture mapping views of the operating room, as shown in figure 4.

3 Port Placement

In robotic MIS, a standard endoscopic configuration composed of a left hand, a right hand and an endoscope is used. An optimization algorithm is used to determine the best entry points from a set of previously segmented admissible ports, such as the intercostal vectors depicted in figure 3(b). The algorithm is based on a semantic description of the intervention, where the main syntactic elements are target points inserted by the surgeon on the anatomical model of the patient to represent the position, orientation and amplitude of the surgical sites, as shown in figure 3(a). The semantics of the intervention are translated into mathematical criteria that are subsequently used in an exhaustive optimization to yield the most advantageous triplet for the patient, intervention and robotic tools under consideration. The criteria and their mathematical formulation are detailed in,[3] they consist of: reachability, dexterity, patient trauma, surgeon effort and factors related to the operative setup. Note that this approach does not depend on the characteristics of the robot, but only on the endoscopic tools. In fact, the same method is currently being used for classical endoscopic interventions (nephrectomy and prostatectomy). Variations to the above configuration can be accommodated either by bypassing the optimization process or adapting it. For instance a fourth port is sometimes used to pull or stabilize an anatomical entity, in which case a segregation in the target vector can be used to assign different role to different tools, while the overall mechanism remains unchanged.

Experimental trials on plastic models have already shown encouraging results,[5] and animal trials are currently being conducted to validate and improve the criteria in use.

4 Robot Positioning

Positioning a surgical robot in a typically cluttered operating room for optimal operation is a challenging task. Surgical manipulators are generally designed to have a flexible structure to adapt to the operating environment, and thus have a high number of degrees of freedom (dofs) to position. In mini-invasive interventions, they are also usually subject to additional spatial constraints which are to fixed points that correspond to the entry ports on the patient's skin. Moreover, the planned results should not only guarantee a collision free operation, but should also target a maximum separation form the surrounding ob-

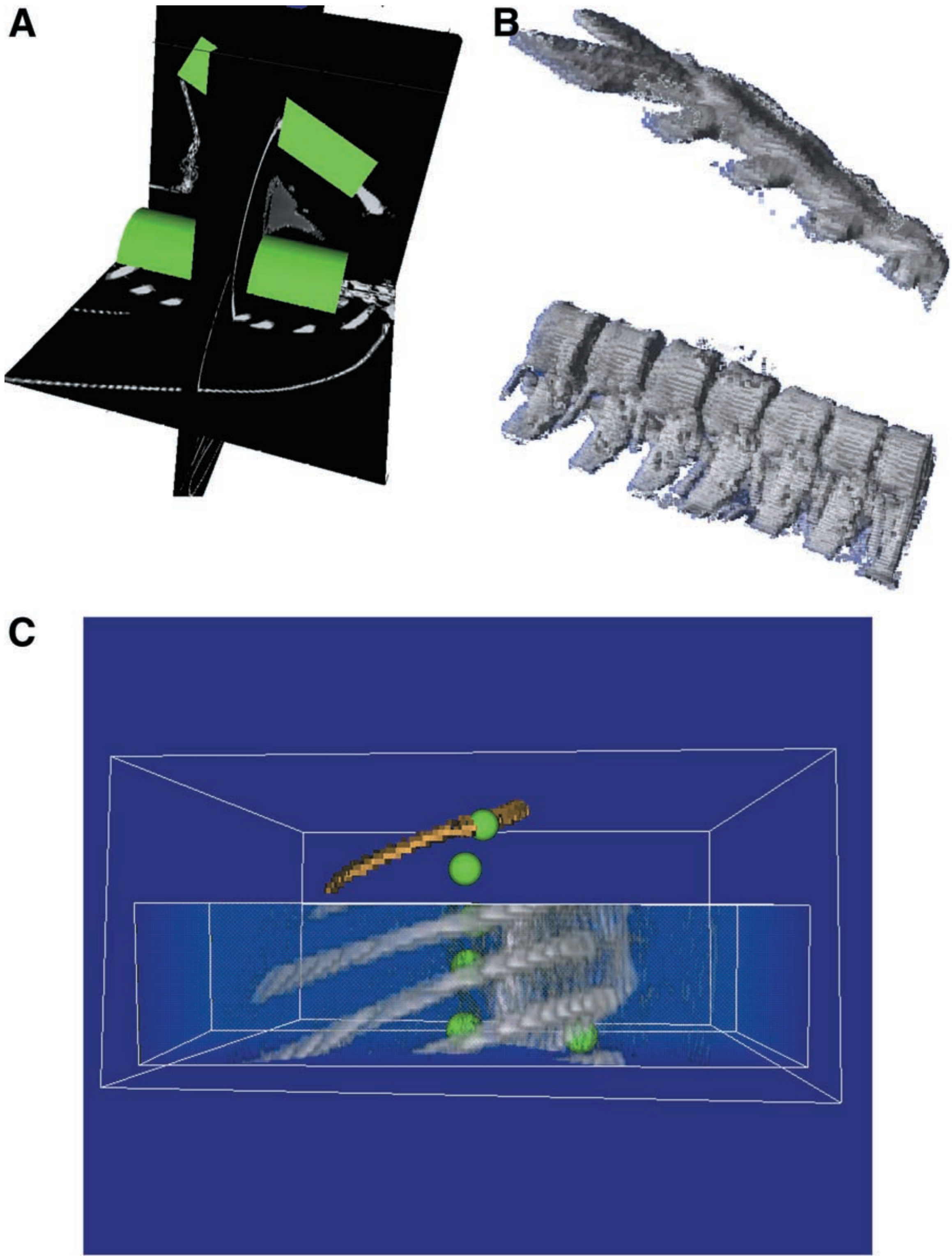

Figure 2. Interactive 3-D segmentation is a successful compromise between versatility and efficiency: (from left to right) 3-D manual segmentation of the sternum and backbone, the resulting reconstructed image and an interactive rib growing operation on a volume rendered image.

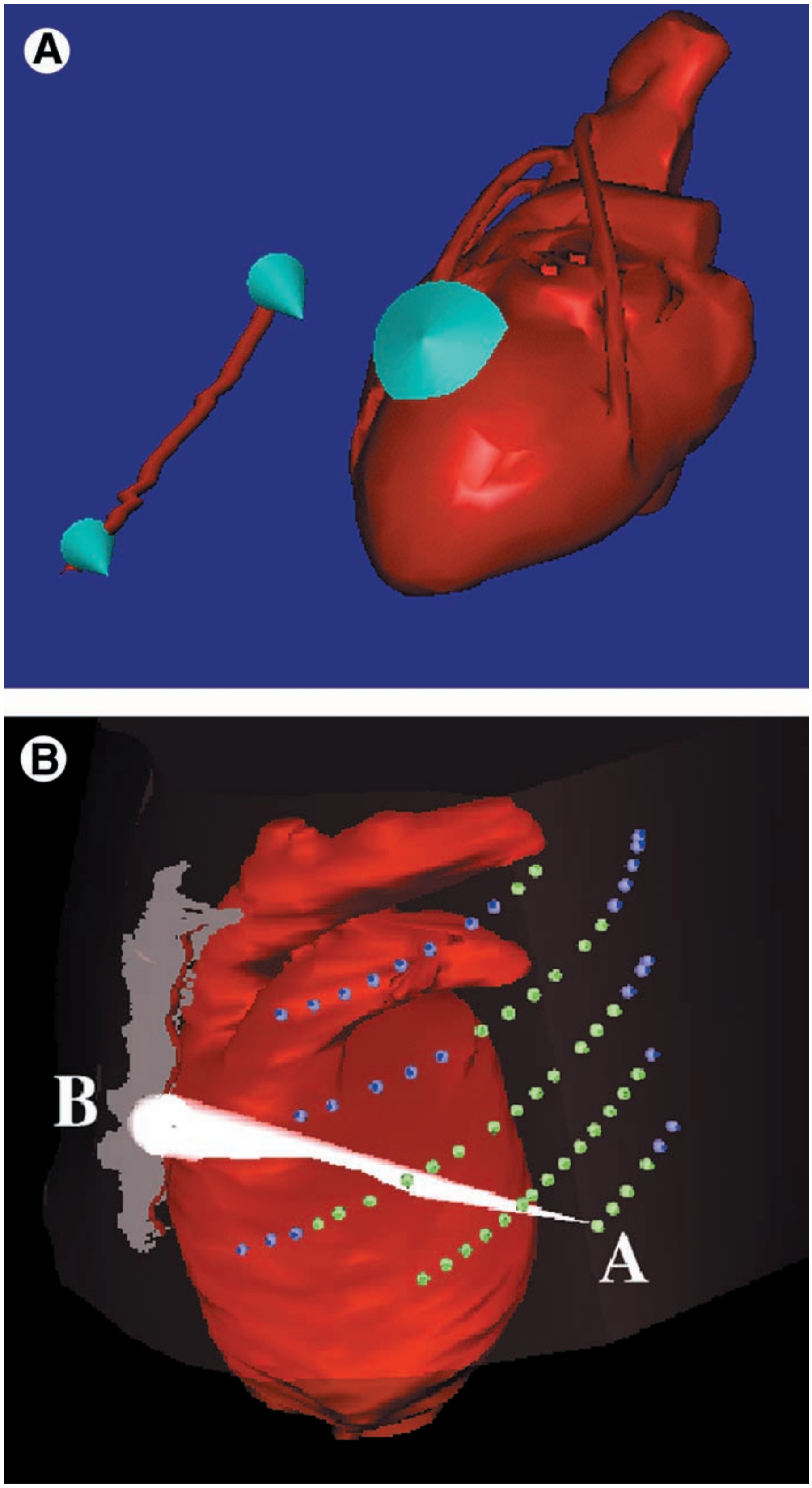

Figure 3. Optimal port placement: (A) Main syntactic elements (B) Example of a reachability test.

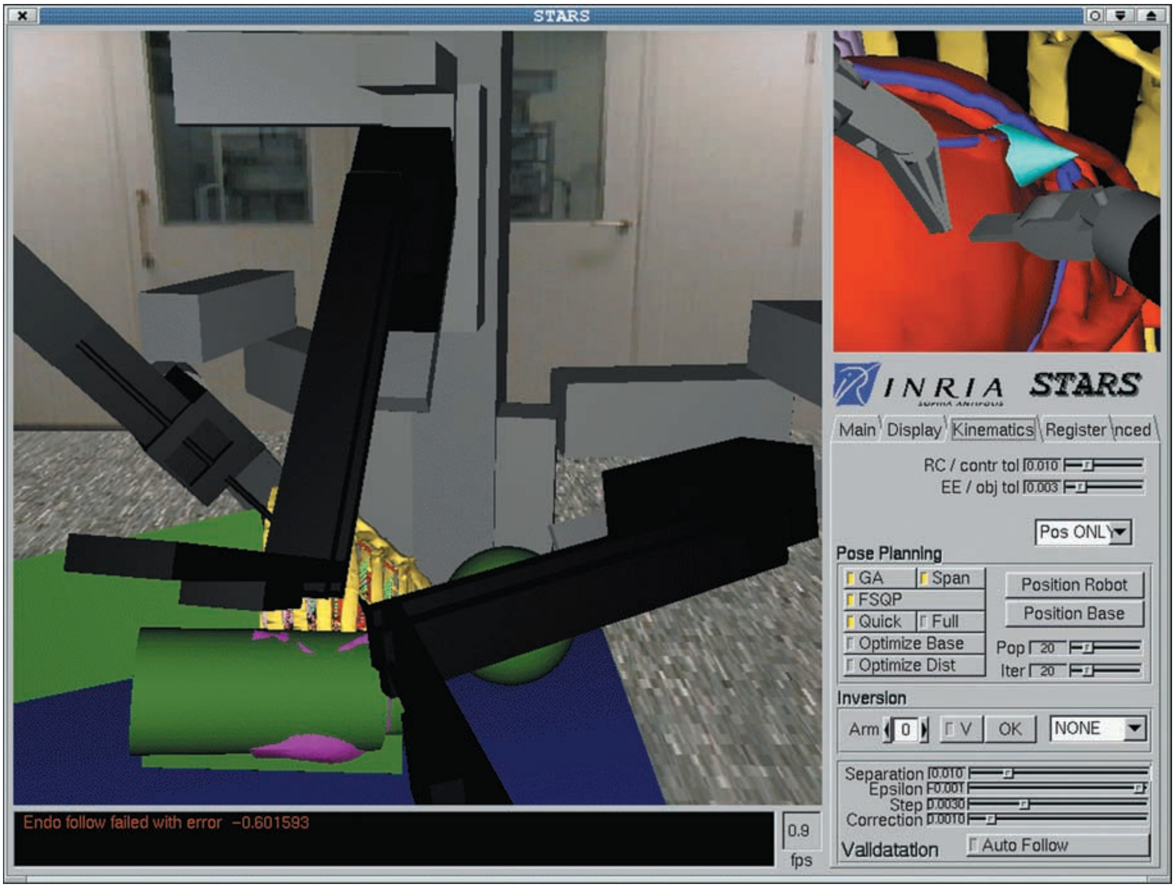

Figure 4. The da Vinci(TM)robot in a coronary artery bypass graft simulation.

stacles, since this is a critical application, and since the positioning is done in an error prone environment.

A systematic method for the positioning of the passive dofs of a robotic system has been developed and is detailed in.[1] Passive dofs are those not under direct tele-operation or autonomous control, they include the position of the base with respect to the operating environment and the patient, and may also include additional setup joints, as illustrated in figure 4 for the Da Vinci™ robot.

5 Verification

As computer integrated robotic systems become more complex and integrated, the risks that accompany such an evolution are inevitably increasing. In particular, both the logical behavior and the processing capabilities of the systems tend to become difficult to analyze. The main goal behind this verification step that precedes the intervention is to look for problematic states in which the system could be trapped. A preemptive approach based on a synchronous finite state machine representation is used. Preliminary analysis is being undertaken to adapt previous work in calssical robotics[4] and assess the needs for modifying the existing approach to better fit medical robotics. Moreover, algorithmic aspects of critical parts of the system (eg, collision detection) are formally proved using a logical assistant system,[8] thus guaranteeing correct behavior both in planning and while execution.

6 Simulation

Simulation serves the two subtly different goals of training and rehearsal of surgical procedures. Simulation for training concentrates on teaching surgeons the different interventional strategies, as well as getting them accustomed to the surgical tools they will be using. Standard pathological cases and physiological complications can be included in instructive scenarios. On the other hand, simulation for rehearsal is a patient dependent validation and preparation of planned goals in settings that come as close as possible to those of the operating theater. This kind of simulation gives the surgeon the possibility to try out different strategies for his intervention, different tools, different positions of the patient, etc. Naturally, patient dependent teaching is also possible. For the purpose of robotic surgery, rehearsal simulation is more interesting; however, it is more difficult to achieve. Indeed, the nonuniformity of the data requires a large amount of preprocessing to give results as good as those found in a premodeled and precalculated simulation system. Therefore, realism is often compromised for efficiency and accuracy.

Standard 3-D input devices (space mice, PHANTOM™ arms or the original input console of the system) are used to control the robots, whereas external and endoscopic views are provided through a rendering interface with possible stereoscopic output. Collision detection is possible between the robot and any modeled obstacle, which can include other parts of the robot (eg, multiple arms) or modeled parts of the patient. Interaction between the tools and the segmented anatomical entities range from simple destruction (eg, figure 4) to elastic deformation using techniques from.[6] Active force constraints, which can prevent and guide the surgeon's motion can also be added using scalar distance fields around the regions of interest. These operations require an increased level of data preprocessing.

7 Transfer

Precision is one of the most important advantages robots bring into the operating room. However, what we are looking for is patient benefit; ie, both precision and accuracy [figure 5] in the accomplishment of either the preplanned tasks or the operated movements of the robot. This consolidation is made possible through registration between preoperative and intraoperative models, as well as between the robot, the patient and the environment [figure 6]. Moreover, during the intervention the accuracy should constantly be monitored through proper tracking.

8 Execution with Augmented Reality and Monitoring

On-line interference evaluation and augmented reality are major safety and efficiency additions to MIS robotic systems. A minimum separation between critical parts of the robotic system is constantly monitored during the intervention, enabling proper preventive actions to be taken (eg, alarm system). This simple safety test is being evolved to a logical supervision system using the techniques introduced in section 5.

At the same time the surgeon is guided through intraoperative clues that help in endoscopic navigation and offer him an overlay of pertinent preoperative information. The possibilities offered by augmented reality are boundless, especially in minimally invasive surgery, where reduced visibility is a major concern. For example in endoscopic CABG interventions, a view of the operating field (3D with the Da Vinci™ system) enhanced with a 3D model of the coronary tree built from angiography acquisitions will make the work easier for the surgeon (see[7]).

Both the monitoring and execution help can be performed locally or from a remote location provided appropriate throughput and delay times are respected. A particular acquisition system is implemented in the system to serve as a transparency layer between low level API (Application Programming Interface)drivers and higher level data access commands from the clients. This setup has been implemented for the da Vinci™ system and used on the hospital LAN and between the hospital in Paris and the research center in Sophia-Antipolis (1000 km distance with 1 Gbits/s throughput and a nominal delay of 10 ms).

9 Analysis

The settings and history of the intervention are conserved by recording the articular values of the robot, the endoscopic images and all the registration information between the patient, the robot and the rest of the modeled entities in the operating theater. The intervention can then be "replayed," shared, criticized, etc. On the long run, the major advantage of such an analysis will appear. Namely, the planning results can be correlated to the outcome of the interventions and revisited to improve the optimization. The same argument also applies

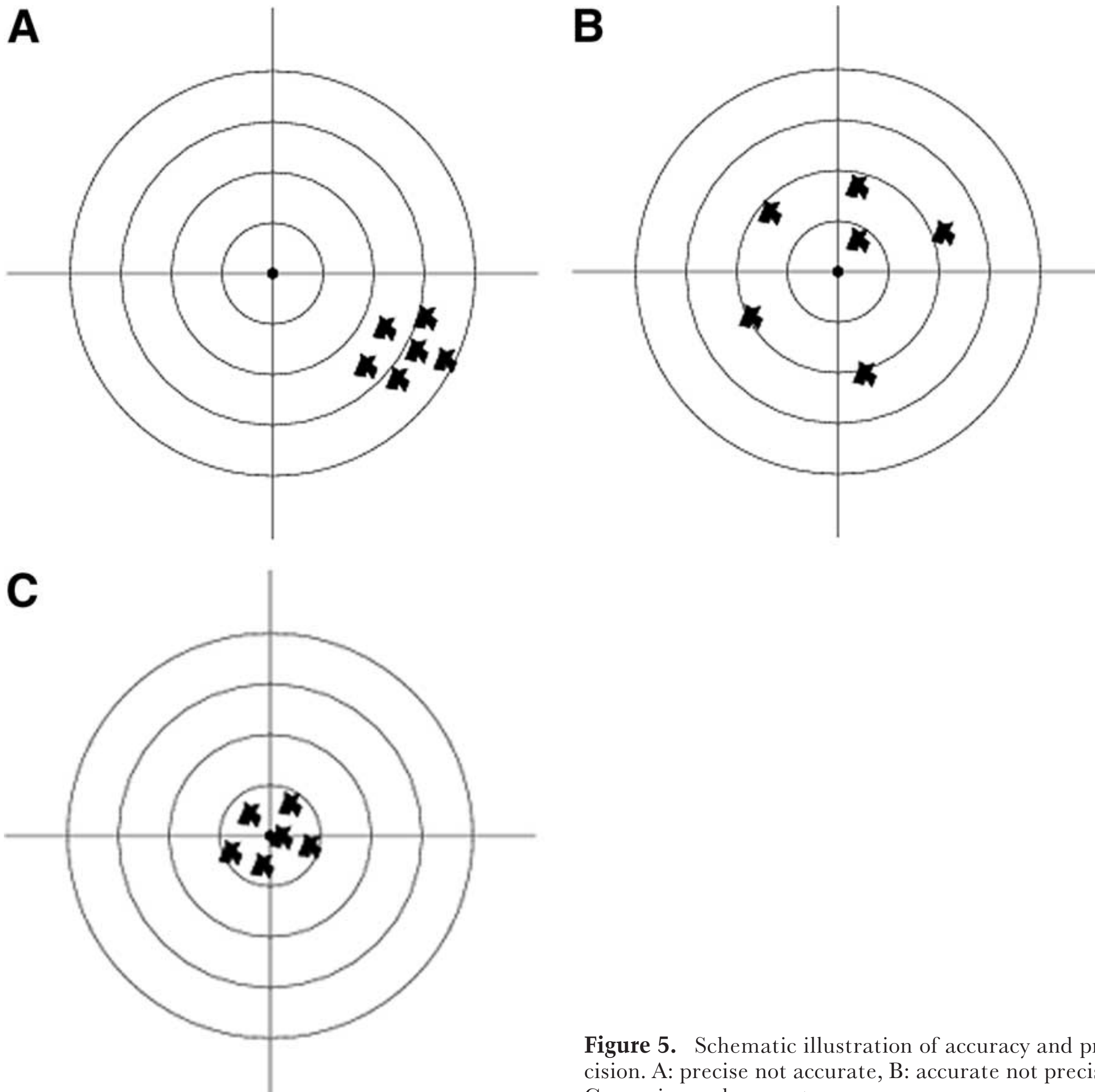

Figure 5. Schematic illustration of accuracy and precision. A: precise not accurate, B: accurate not precise, C: precise and accurate.

to the rest of the execution steps, where critical chains can be isolated and enhanced.

10 An In Vivo Clinical Validation: Transfer Precision in the Operating Room

The experiments described in this section concern the totally endoscopic CABG intervention performed on a live dog. The entire intervention is performed through incisions in the chest wall, where carbon dioxide is insufflated and the left lung is collapsed, thus enabling the movement of the instruments. The da Vinci™ surgical system, operated in a special API mode that enables precise readings of the state of the robot and the endoscopic images, is used to operate a dog.

The description of the experiment concentrates on analysing the transfer of the planned results into the operating theater and augmented reality first results. If unproperly performed, the transfer could invalidate any claimed optimality. The transfer consists of the following intraoperative steps: register preoperative models to the patient, register the robot to the patient, locate the planned ports on the patient, and give the robot the planned posture. Then, the good realization of the transfer also conditions the accu-

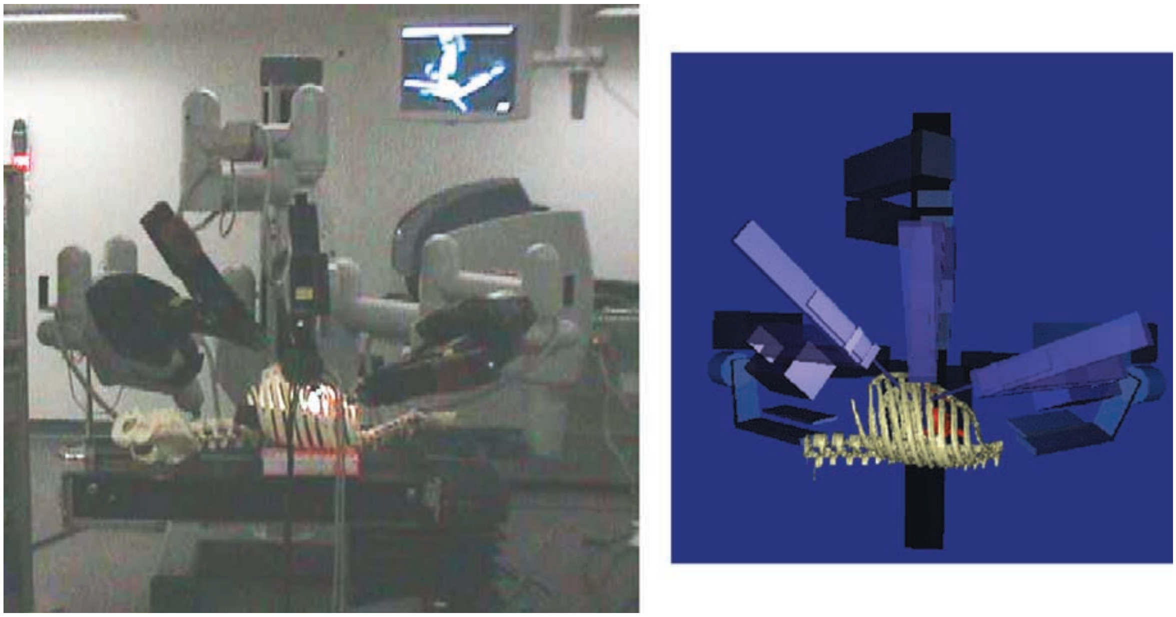

Figure 6. Transferring planned results to the operating theater after proper registration steps: first validation on a plastic phantom.

racy of the information overlay in the endoscope for augmented reality results.

10.1 Preoperative Processing and Planning

Two sets of CT scans where acquired and processed to obtain surface models of the heart of the dog, the bones, LIMA (artery used for the bypass) and the skin, as shown in figure 7, on which the surgeon modeled the intervention through target cones on the heart and on the LIMA. The planning is performed as described section 3 and 4, to obtain optimal placement of the ports and the corresponding collision free position of the robot (figure 6).

10.2 Registration

The registration step is twofold: register the preoperative images (on which the planning results have been obtained) to the patient in intraoperative position, then register the robot to the patient. We have chosen a fiducial based registration because it is a simple and efficient registration technique. The configuration of the markers should minimize any potential variations between their preoperative and intraoperative positions; eg, privileging stiff locations such as on the bony structures.

Twelve fiducial markers were manually identified on the CT scan and pointed by one of the robotic arms after the dog had been positioned on the operating table, as shown in figure 9. A rigid transformation is then sought in a least-square sense relating the two coordinate frames: the patient coordinate, which is that of the preoperative images and the remote coordinate frame, which is that of the robot. The obtained RMS error was 19 mm, which is considerably higher than previously observed on plastic phantoms errors, which were typically lower than one centimeter. Looking back at the assumptions behind using a one step rigid transformation and at the measurement process, it is unlikely that the CT scan reconstruction caused the above error, due to the quality of the latter. The same applies to the precision of the robot, which was calibrated before the experiment. Indeed, this step registers the robot directly to the CT scan model, thus implicitly neglecting any nonrigid transformation between the scan and the intraoperative dog position. This relatively high error is the counterpart of the simplicity and noninvasiveness of this marker based registration.

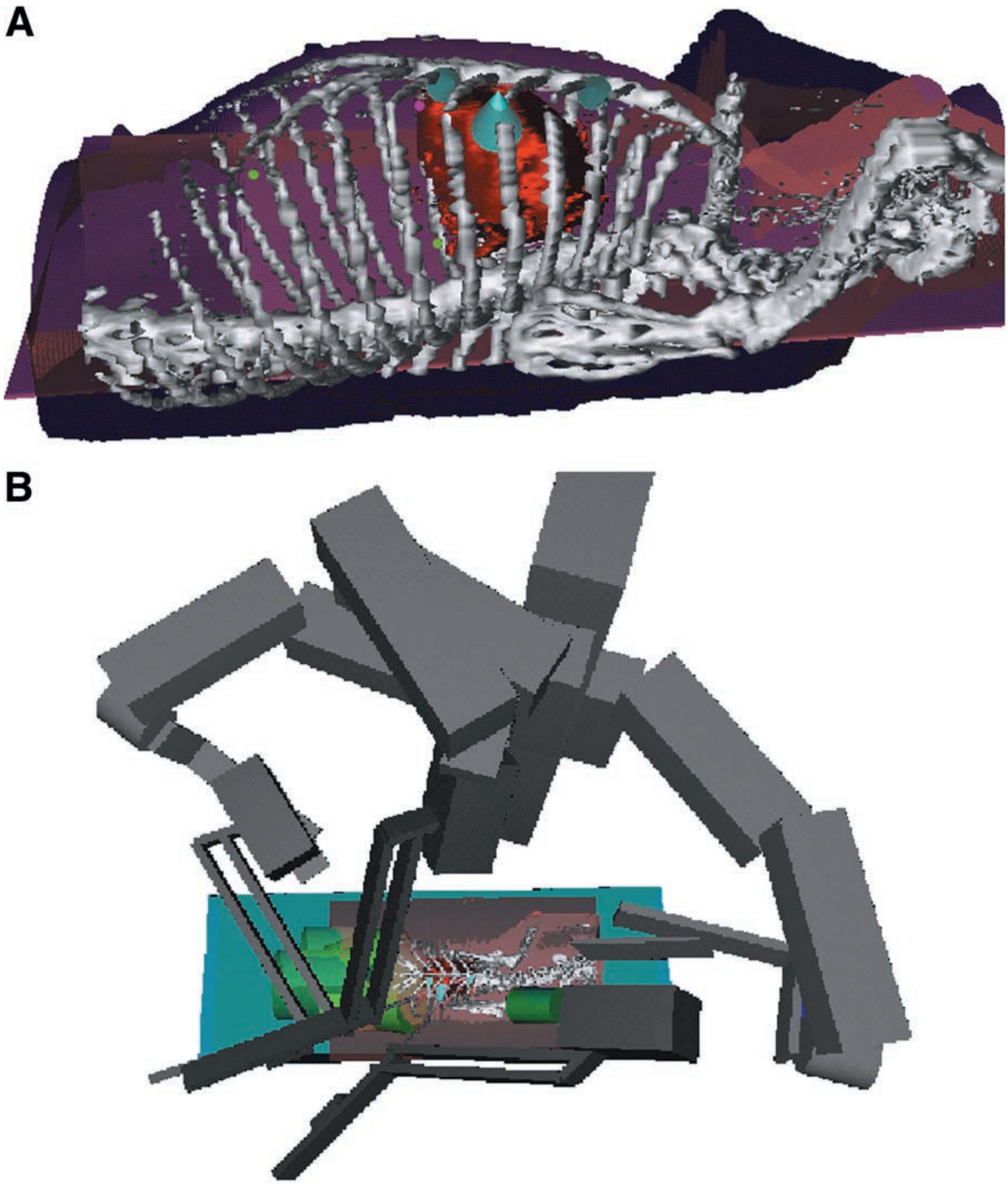

Figure 7. Intervention planning: A, dog anatomy and optimal port placement, B, optimal robot position.

10.2.1 Error Measurements

To better discriminate the different sources of error, a new registration was performed after the insufflation, which introduced a deformation of the rib cage on which the fiducials are distributed. The obtained error was of 20.1 mm, which is comparable to the original error before the insufflation, insinuating that the deformation is within the precision of the registration.

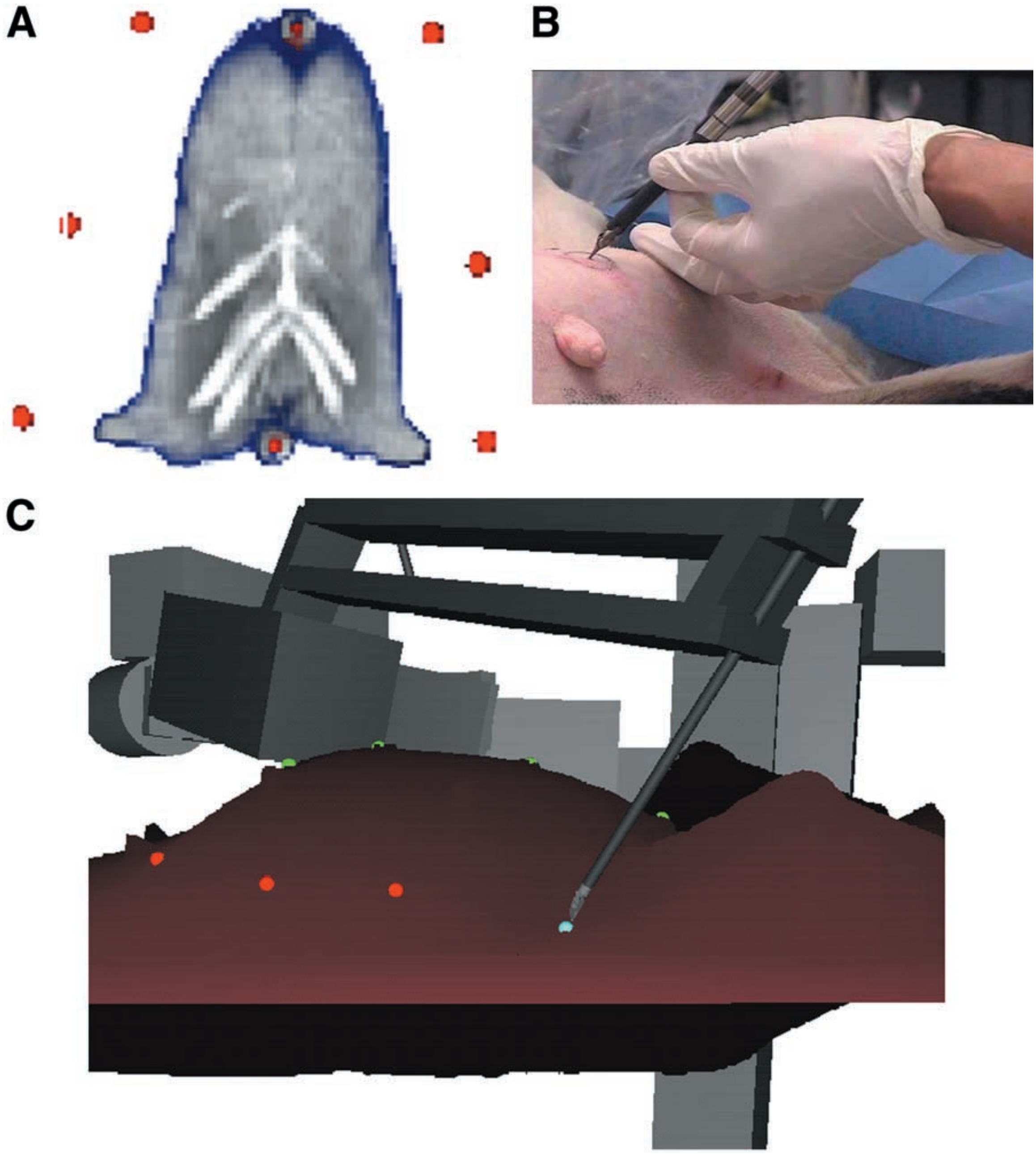

Figure 8. Fiducial markers are easily distinguished in preoperative CT images (A). Pointing fiducial markers with the robot tool tip (B and C).

10.3 Port Placement

Once the robot is registered to the patient, the planned ports (as described in section 3) must be transferred on the patient's skin. The robot is here used as an interactive pointer. The planned ports are expressed in the robot coordinate frame and used to guide the user who will manipulate the end effector as a pointing device, as shown in figure 7. The precision of this approach is limited by that of the registration, as well as the ability of the operator to move the pointing device (the arm end effector). Moreover, the ports should be in an area where the result of the registration remains valid. In other words, the placement of the fiducial mark-

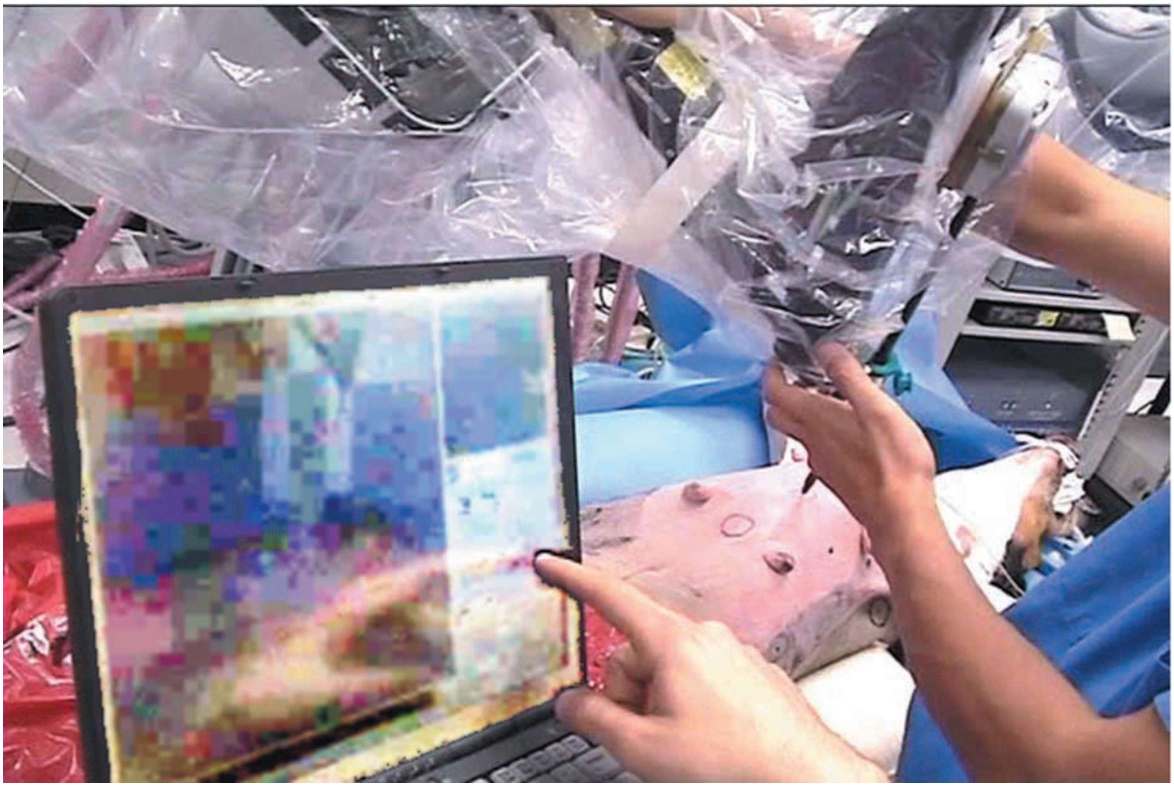

Figure 9. Interactive guidance: A radar like X-Y and depth indication of the desired port with additional error information is constantly displayed.

ers should take into account a desirable proximity with the potential position of the ports.

As shown in figure 10, an interactive interface is used to continuously display the error vector between the position of a desired port and one of the arms of the robot. The surgeon uses this information to move the tool tip of the arm to the incision site. The method was judged (clinically) satisfactory in terms of both efficiency and precision.

10.4 Robot Positioning

The robot was positioned to match the stationary remote centers of the arms with the ports, and to avoid any singular or colliding configuration, as shown in figure 7. This optimization concerned the robot setup joints and the position of base of the daVinci™ system with respect to the patient. The resulting position is shown in figure 9, where there was no collision free solution. Indeed, an automatic validation, where the expected movements of the robot are reproduced after the set-up joints have been fixed, showed that a persistent collision occurs with the lower limbs of the dog (maximum of 11 mm), that no collision occurs between the arms, and that a small collision occurs between one of the arms and the operating table (3.2 mm). The conflict with the lower limbs of the dog is not alarming, since mild pressure (1.1 cm) can easily be tolerated. However, a collision with the operating table would lead to a blocking situation. An easy workaround would have been to allow the rotation of the dog in the pose planning, which would have given more flexibility to the relative positioning between the robot and the dog, thus avoiding the colliding state. Nevertheless, it was decided to keep the current position to confirm the predicted complications experimentally. Indeed, both collisions were observed at the expected sights.

10.5 Augmented Reality

Due to experimental constraints no angiogram was acquired on the dog, thus preventing a total

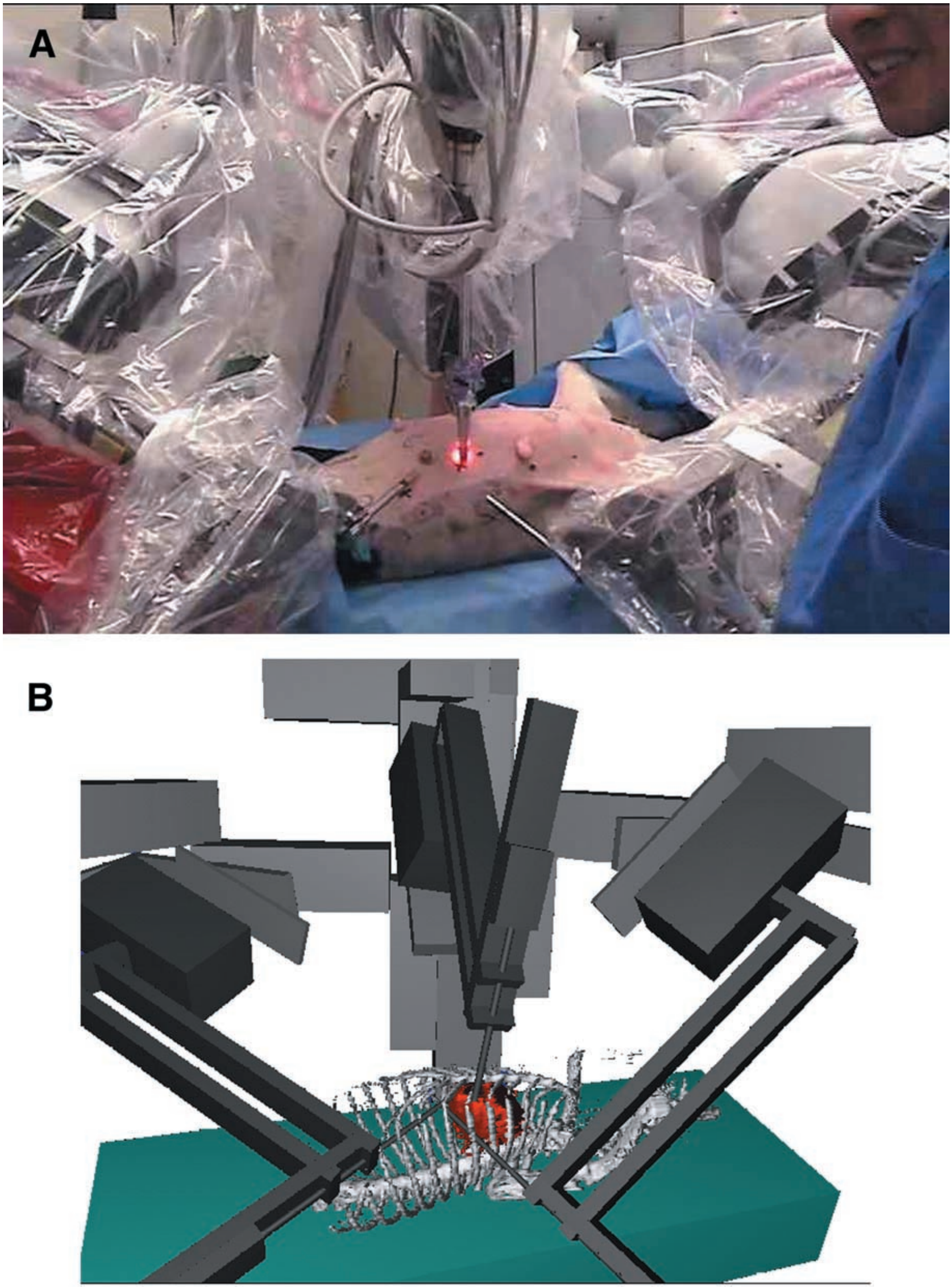

Figure 10. Final ports and positioning of the robot at the beginning of the intervention.

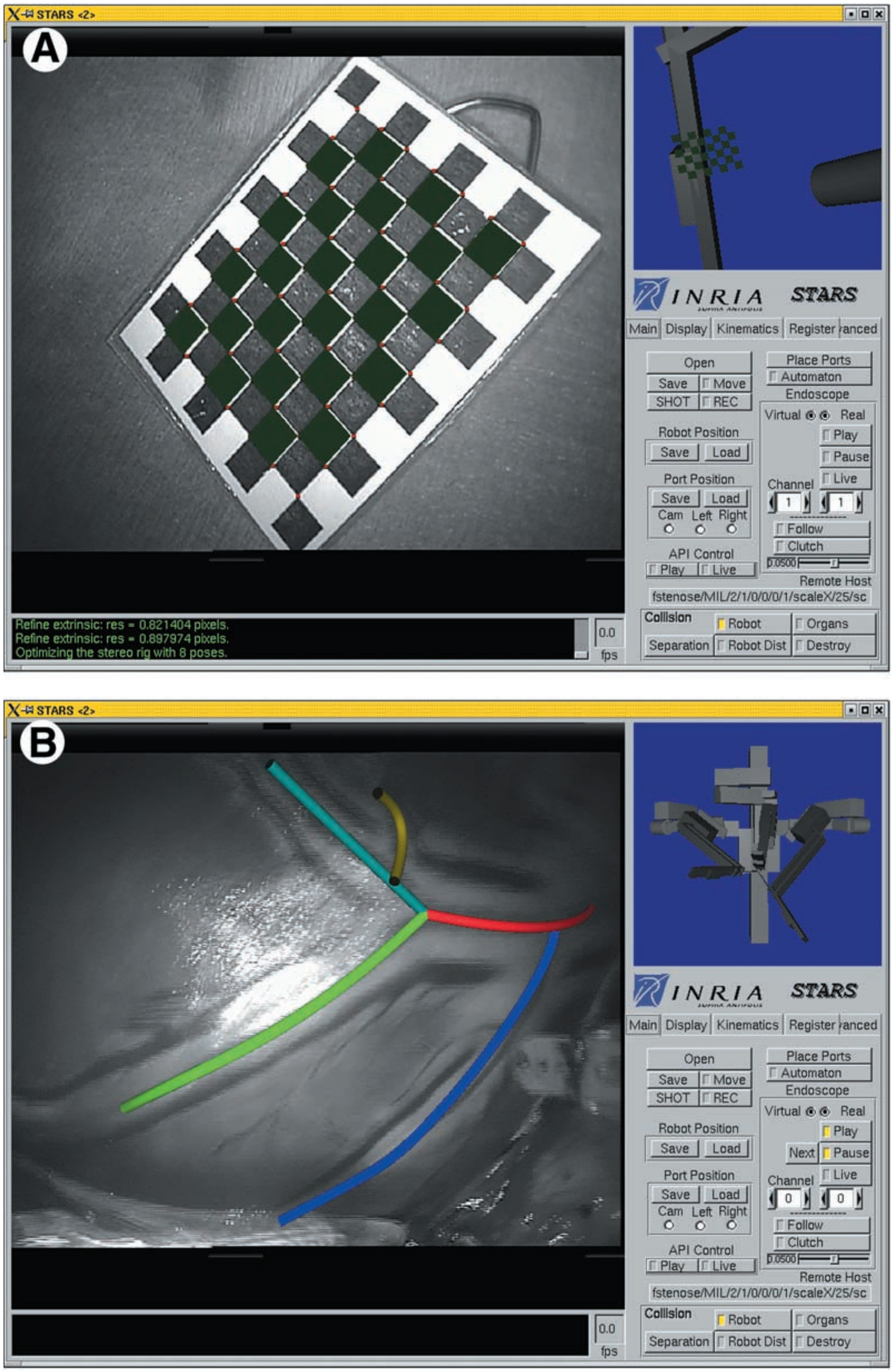

Figure 11. A: reprojection of the calibration grid using the forward robot kinematics; B: 3-D model of the coronary tree built from calibrated endoscopic views.

overlay of preoperative vessels on intraoperative images, in a restricted field of view. Nevertheless, we registered the heart as seen in the endoscope with respect to preoperative data, where section 10.2.1 gives a rough estimate of the shift we can expect.

We propose to interactively solve the registration problem by combining the measures based on automatically extracted reliable landmarks in the intraopeartive image as well as the indications given by the surgeon. The use of the robot kinematics and the superimposition in the endoscopic images assumes that the motorized stereoscopic endoscope is precisely calibrated (see[10]). Indeed, the endoscope was calibrated on data set of about ten pairs of images (as illustrated on figure 11). Using the pose of the endoscope with respect to the grid, the reprojection error was about 0.5 pixels. After estimation of the transformation between the cameras and the endoscope tip, the reprojection error was about 4.5 pixels using the robot forward kinematics. An equivalent error was found by reprojecting the grid with new positions of the endoscope corresponding to its displacement across the operating volume. As a consequence, the displacement of the endoscope deduced from the forward robot kinematics will have to be refined by using intraimages measurements to insure and sustain the precision of the superimposition.

The right part of the figure 11 illustrates the overlay of a coronary tree in the endoscopic images built off-line from the calibrated endoscopic images and reprojected.

11 Conclusions and Perspectives

An overview of the architecture for a computer integrated minimally invasive robotic surgery has been presented. The underlying implementation (Simulation and Training Architecture for Robotic Surgery: STARS) is characterized by its versatility and modularity in what concerns both robotics and medical image processing. STARS is an integrated system for robotics surgery that is used for all the steps described in this paper, ranging from radiological image manipulation to intraoperative registration, going through planning and simulation performed with the surgeon.

Despite the difficulties faced in terms of time limitations and logistics, the performed animal experiment was highly rewarding: the operation was successfully performed according to the transferred planning and the predicted complications were confirmed. It also gave strong support to many of the assumptions built during previous experiments on a plastic phantom, such as the adequacy of the geometric approximations used for the robot and the surrounding obstacles, and unveiled several subtleties that were not accounted for, such as the effect of using a rigid transformation for the registration. Moreover, the time requirements of the transfer methods, summing to under 20 minute, were satisfactory.

Efforts in the near future will focus on analyzing the collected data and correlating the observed errors to the transfer steps and assumptions. Furthermore, the effect of the latter on the planned results and the final outcome of the intervention should be clearly identified. New solutions will also have to be sought to increase intraoperative precision, and deal with the motion of internal organs through tracking techniques for use with augmented reality. The long term goal of the team is develop a computer integrated system to improve the quality of surgical robotic interventions thus achieving maximum patient benefit.

Acknowledgments

In this paper, the authors are the narrators of a larger multidisciplinary effort. Their warmfull thanks go to all the ChIR Medical Robotics Team at INRIA Sophia Antipoplis. Also, this work would not have been possible without the clinical exposure and motivation that Alain Carpentier, his team and Didier Loulmet provided at the Hopital Europeen Georges Pompidou and Lenox Hill Hospital. Finally, a scientific collaboration with the Intuitive Surgical team (France and US) made the animal experiment possible. Also, this work would not have been possible without the clinical exposure and motivation that the Cardiac Team and Didier Loulmet provided at the Hôpital Européen Georges Pompidou and Lenox Hill Hospital. Volkmar Falk and Friedrich Mohr also provided very incitive feedback.

References

1. Adhami L, Coste-Manière È. Positioning tele-operated surgical robots for collision-free optimal operation. In IEEE Int. Conf. On Robotics and Automation, May 2002.

2. Adhami L, Coste-Manière È. A versatile system for computer integrated miniinvasive robotic surgery. In Medical Image Computing and Computer Assisted Intervention (MICCAI'02), to appear, 2002.
3. Adhami L, Coste-Manière È, Boissonnat J.-D. Planning and simulation of robotically assisted minimal invasive surgery. In Proc. Medical Image Computing and Computer Assisted Intervention (MICCAI'00), volume 1935, 2000.
4. Borrelly J.-J., Coste-Manière È, Espiau B, Kapellos K, Pissard-Gibollet R, Simon D, Turro N. The Orccad architecture. Intl Journal of Robotics Research, 17(4), 1998.
5. Coste-Manière È, Adhami L, Severac-Bastide R, Lobontiu K, Salisbury A, Boissonnat J.-D., Swarup N, Guthart G, Mousseaux É, Carpentier A. Optimized port placement for the totally endoscopic coronary artery bypass grafting using the da Vinci robotic system. In Lecture Notes in Control and Information Sciences, Experimental Robotics VII, volume 271, 2001.
6. Cotin S, Delingette H, Ayache N. Realtime elastic deformations of soft tissues for surgery simulation. IEEE Trans. On Visualization and Computer Graphics, 5(1), 1999.
7. Devernay F, Mourgues F, Coste-Manière È. Towards endoscopic augmented realityfor robotically assisted minimally invasive cardiac surgery. In IEEE, editor, Proc. Medical Imaging and Augmented Reality, pages 16-20, 2001.
8. Huet G, Kahn G, Paulin-Mohring C. The Coq Proof Assistant : A Tutorial : Version 7.2, 2002.
9. Loulmet D, Carpentier A, d'Attellis N, Berrebi A, Cardon C, Ponzio O, Aupècle B, Relland JY. Endoscopic coronary artery bypass grafting with the aid of robotic assisted instruments. The journal of thoracic and cardiovascular surgery, 118(1):4-10, 1999.
10. Mourgues F, Coste-Manière È. Flexible calibration of robotized stereoscopic endoscope for overlay in robot assisted surgery. In Medical Image Computing and Computer Assisted Intervention (MICCAI'02), to appear, 2002.