Planning and Simulation of Minimally Invasive Surgery using Tele-Operated Manipulators

Louaï Adhami, Ève Coste-Manière, Jean-Daniel Boissonnat

{Louai.Adhami, Eve.Coste-Maniere, Jean-Daniel.Boisonnat}@sophia.inria.fr

ChIR Medical Robotics Team, INRIA Sophia-Antipolis, France

http://www.inria.fr/chir

SUMMARY OF THE TALK

This talk presents a framework for preparing and executing Minimal Invasive Surgery (MIS) using tele-operated robotic manipulators. The approach consists of a planning, validation, simulation, transfer, monitoring and analysis phase. The goals of each phase is, respectively, to propose suitable incision sites for the robot and the position of the latter in the operating theater, to automatically validate the proposed settings, to enable a realistic simulation of the intervention suitable for training, to transfer the planning results in the operating room (OR), to monitor the progress of the intervention and finally to archive and analyze them.

With the patient's pre-operative data, we formulate the needs of the surgeon and the characteristics of the robot as mathematical criteria in order to optimize the settings of the intervention. Then we automatically reproduce expected surgeons' movements and guaranty their feasibility. We simulate the intervention, paying particular attention to potential collisions between the robotic arms. If satisfactory, the obtained results are transferred to the operating room by first registering the pre-operative data of the patient with his current position, and then registering the robot with respect to the patient. During the intervention, it is possible to monitor (possibly from a remote location) the goings of the intervention and to predict potential complications such as a collision with the robot. Finally, the intervention is archived by storing the position of the robot as well as endoscopic/external images, on which further analysis can be carried out to measure the efficiency of the robotic system and the chosen settings.

INTRODUCTION

In order to obtain maximum utility of a robotic system used in MIS, two key settings have to be correctly established: the entry points of the robotic instruments on the patient, and the position of the robot with respect to the patient in the operating theater.

The extension of MIS techniques to use robotics came from the limitations imposed on the surgeon by manually controlled MIS instruments. Namely, the surgeon finds his movements, vision and tactile sensing reduced and severely altered ([6],[7]). The introduction of robotic manipulators would remedy the loss of dexterity in the movements by incorporating additional degrees of freedom at the end of the tools; i.e., in the part that would be inside the patient. In addition, more precision and better tactile feedback can be achieved by proper design of the system, which can also improve the hand-eye alignment of the surgeon and offer better 3d visualization.

However, this innovation has its own limitations and problems. Beginning with the limitations, and despite the increased dexterity, the region reached from a set of incision sites will remain restrained, thus these sites have to be carefully chosen for each patient depending on his anatomy. Moreover, the forces that can be delivered by a robotic manipulator may vary significantly with the position of the latter, which stresses even more on the choice of the incision sites or *ports*. Now moving to the problems introduced by the use of a robot, and setting aside classical control and liability concerns, the main handicap of such systems is the issue of potential collisions between the manipulator arms. Again this necessitates the proper positioning of both the incision ports and the robot. Finally, and no matter how intuitive the controlling device is made, the surgeon will need time and proper training before using his new "hands" in the most efficient way. Therefore simulation would be used to rehearse the intervention, validating the planned ports and helping the surgeon get accustomed to both his tools and his patient. In addition, generic case studies can be used for training purposes.

RELATED WORK

The use of computer assisted systems in the preparation and simulation of minimally invasive techniques is being recognized as an efficient tool in surgery. Various successful systems have been proposed and are already operational. Some examples are the haptic system based on the work of [8], the more general purpose system in [5], and [9] in neurosurgery. These systems do not handle teleoperated robotics, with the notable exception of the KISMET [3] simulation tool that is being merged with the ARTEMIS [1] robotic environment, but which lacks systematic planning.

In [10] the authors plan a minimally invasive CABG with the Zeus system of Computer Motion [4]; however, they do not integrate the models of the robot in the planner and rely on empirical results from [11] for the port placement.

To the best of our knowledge, there is no system that integrates the planning, simulation and online control of a robotic surgery system for laparoscopic or cardiac MIS interventions.

REFERENCES

[1] ARTEMIS homepage. http://wwwserv2.iai.fzk.de/artemis/.

[2] da Vinci[tm] surgical system. http://www.intusurg.com/html/davinci.html.

[3] KISMET 3d-simulation software. http://iregt1.iai.fzk.de/.

[4] ZEUS[tm] robotic surgical system. http://www.computermotion.com/zeus.html.

[5] U. Kühnapfel, H.K. Çakmak, and H. MaaSS. 3Dmodeling for endoscopic surgery. In *Proc. IEEE Symposium on Simulation*, pages 22–32, Delft University, Delft, NL, October 1999.

[6] Didier Loulmet, Alain Carpentier, Nicolas d'Attellis, Alain Berrebi, Cyril Cardon, Olivier Ponzio, Bertrand Aupècle, and John Y. M. Relland. Endoscopic coronary artery bypass grafting with the aid of robotic assisted instruments. *The journal of thoracic and cardiovascular surgery*, 118(1), July 1999.

[7] G. B. Cadière and J. Leroy. *Principes généraux de la chirurgie laparoscopique. Encycl Méd Chir (Techniques chirurgicales - Appareil digestif)*, volume 40, page 9. Elsevier-Paris, 1999.

[8] Stéphane Cotin, Hervé Delingette, and Nicholas Ayache. Real-time elastic deformations of soft tissues for surgery simulation. *IEEE Transactions On Visualization and Computer Graphics*, 5(1), January 1999.

[9] L.M. Auer, A. Radetzky, C. Wimmer, G. Kleinszig, H. Delingette, and B. Davies. Visualisation for planning and simulation of minimally invasive procedures. *Lecture Notes in Computer Science*, 1679:1199–1209, September 1999.

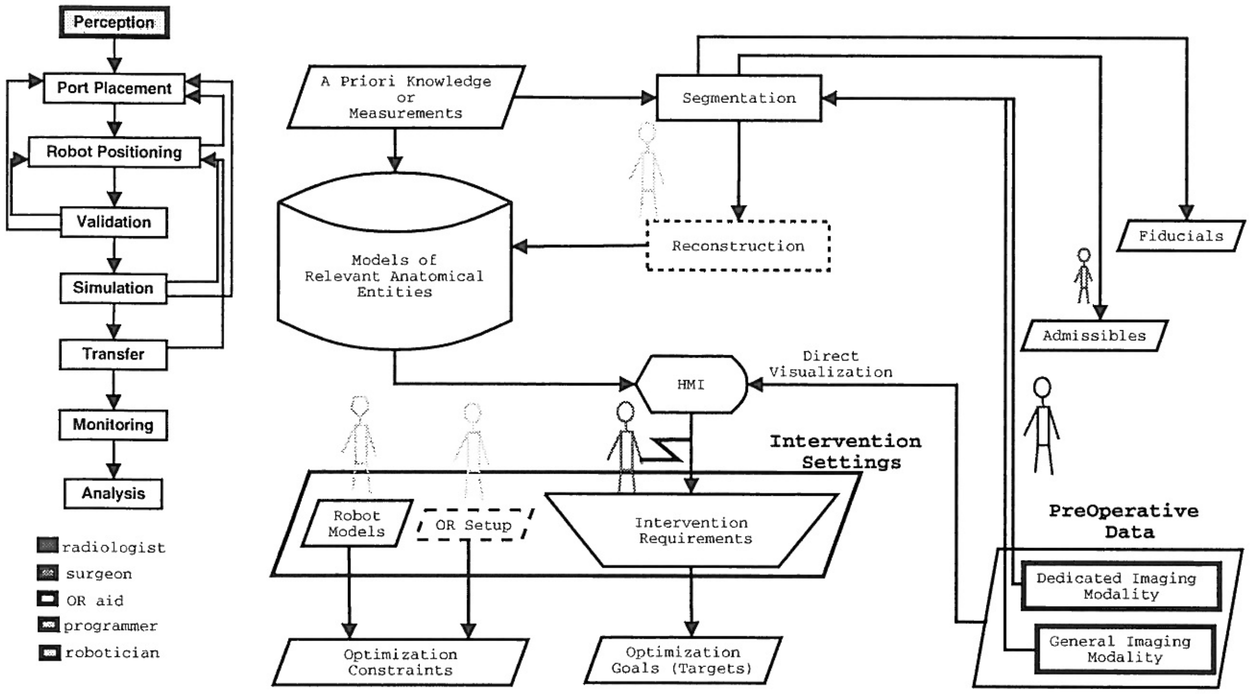
[10] A. M. Chiu, D. Dey, M Drangova, W. D. Boyd, and T. M. Peters. 3-d image guidance for minimally invasive robotic coronary artery bypass. Heart Surgery Forum, http://www.hsforum.com/vol3/issue3/2000-9732.html, 2000.

[11] Harold Tabaie, Jeffrey Reinbolt, Peter Graper, Thomas Kelly, and Michael Connor. Endoscopic coronary artery bypass graft (ECABG) procedure with robotic assistance. *The Heart Surgery Forum (http://www.hsforum.com)*, 2(0552), September 1999.

[12] Jean-Daniel Boissonnat and Frédéric Cazals. Natural neighbour coordinates of points on a surface. Technical Report 4015, INRIA-Sophia, 2000.

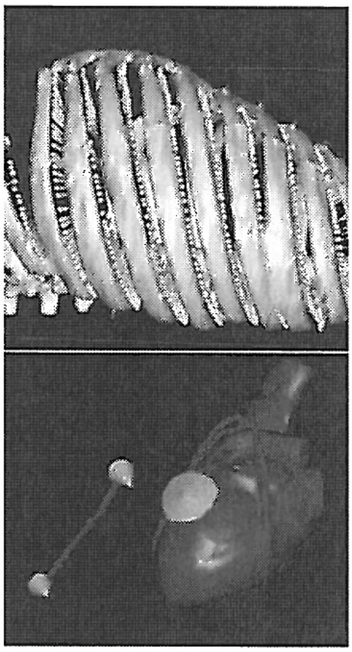
[13] Ève Coste-Manière, Louaï Adhami, Renaud Severac-Bastide, J. Kenneth Jr. Lobontiu, Adrian Salisbury, Jean-Daniel Boissonnat, Nick Swarup, Gary Guthart, Élie Mousseaux, and Alain Carpentier. Optimized port placement for the totally endoscopic coronary artery bypass grafting using the da Vinci robotic system. In *Lecture Notes in Control and Information Sciences, Experimental Robotics VII*, to appear.

PERCEPTION



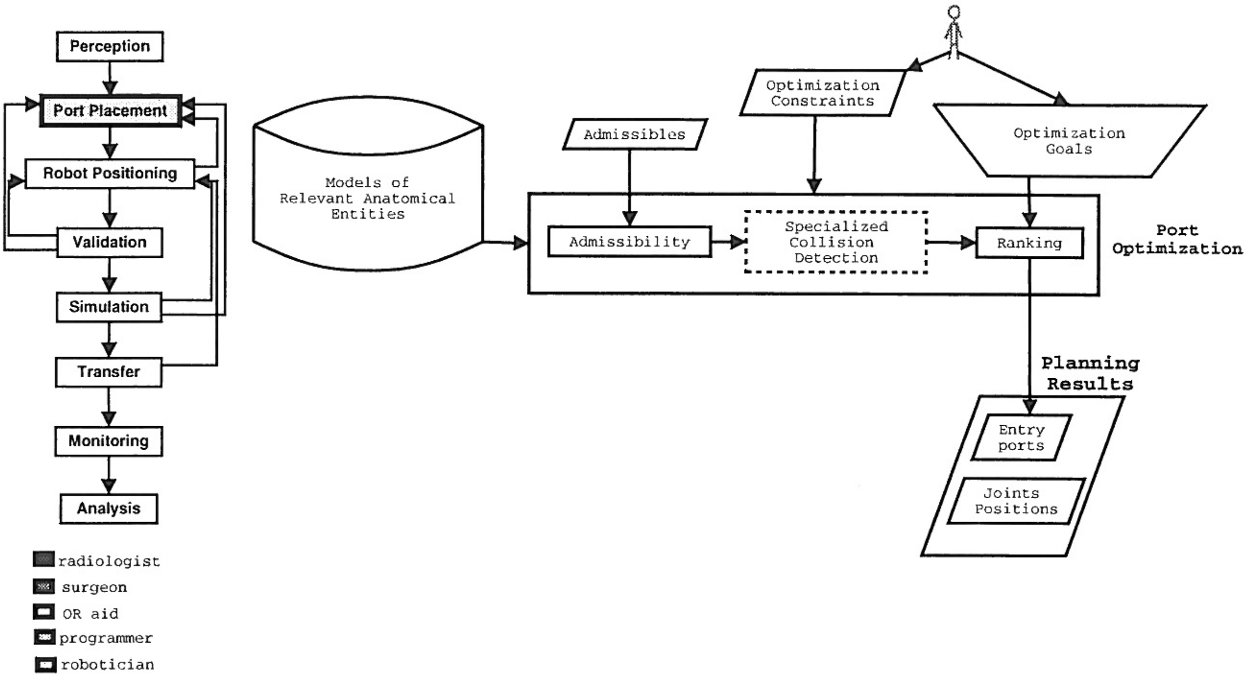
To efficiently plan the surgical procedure and make the best use of the robot, patient dependent information has to be combined with the specifications of the robot and the settings of the operating theater to yield a realistic description of the intervention.

In the first stage the necessary information about the patient is collected and processed. These are usually 3d pre-operative radiological data that may come from one or more acquisition modalities. The data can be segmented and reconstructed to obtain surface models that are more flexible in terms of visualization and modeling. Alternatively, direct methods such as direct volume rendering or slicing can be used to manipulate the data. In all cases, two mandatory outputs should be extracted from the pre-operative data, namely, the *admissible* and the *fiducial* sets.



The admissible set describes the location of all possible entry points of the robot along with the corresponding direction at each point, which is usually perpendicular to the patient's skin. The process of generating admissible points is automatic and can be complex in some cases such as cardiac surgery, where intercostal spaces have to be detected. Fiducial markers are needed for the registration step that allows the execution of the planned result in the OR. They serve to establish a precise correspondence between the pre-operative data and the position of the patient on the operating table. Moreover, the fiducial markers can be used to register the robot to the patient as detailed in the transfer step.

In the second stage, a model of the robot; i.e., its kinematic and physical structure, is combined with a model of the operating theater to define a set of constraints on the positioning and the movement of the robot. The surgeon then describes the surgical procedure using an appropriate interface that contains the models of the relevant anatomical entities. On those he specifies weighted *target* areas and directions on locations of interest; e.g., a tumor or an anastomosis point.



Triplet Optimization

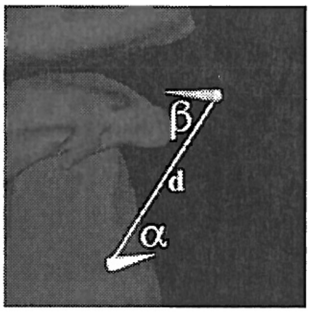
An exhaustive search for a triplet that insures the best accessibility of the tools amongst the admissible points is carried out. In the first step, the following criteria are used to segregate the possible incision sites.

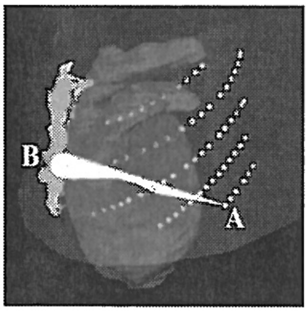
☐ The length of the tool between a target and an admissible point (d) should be in a given range. If the incision is too close, then dexterity is lost, and if it is too far, the target will be out of reach (only the lower limit on d is considered in the case of the endoscope).

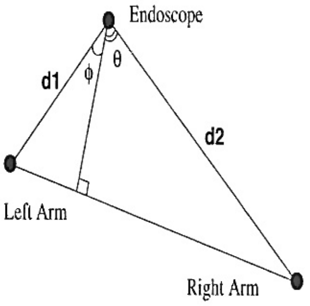
☐ The angle between the admissible direction and the line relating the target to the admissible point (β) should be smaller than a given limit, above which the tool can hurt the patient. For instance, an angle of more than a given value can cause severe trauma to the adjacent ribs.

☐ The angle between the target direction and the line relating the target to the admissible point (α) should be as small as possible. This measure translates the ease with which the surgeon will be able to operate the concerned target areas from a given port with a robotic tool, or the quality of viewing these areas with an endoscope (depending on its angle).

☐ The path between the admissible point and the target area should be clear; i.e., not hindered by an anatomical structure.

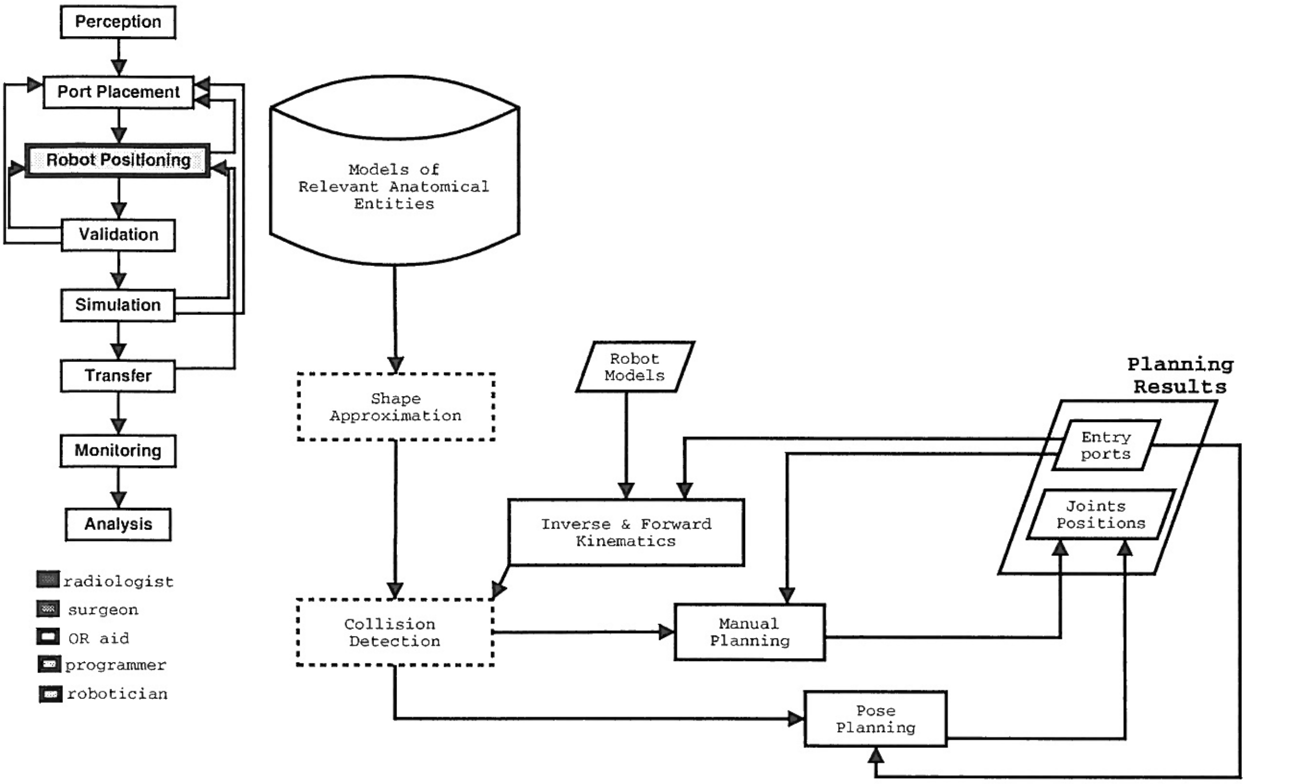






After the elimination of unusable admissible points, and the ranking of the others, a triplet is sought to insure the symmetry of the left and right arms with respect to the endoscope, favoring positions further away from the endoscope to give a clear field of view (formally this corresponds to maximizing ϕ and θ). This optimization is exhaustive to insure the completeness of the obtained solution; however, it does not cause a performance problem since the search is hierarchical and thus only a small number of admissible points are left for ranking after all the tests have been performed.

ROBOT POSITIONING



Once a suitable port placement has been found, the robot has to be positioned in a way that avoids collisions between its arms, in addition to other constraints such as an out of reach motion. The positioning problem can be further broken down into:

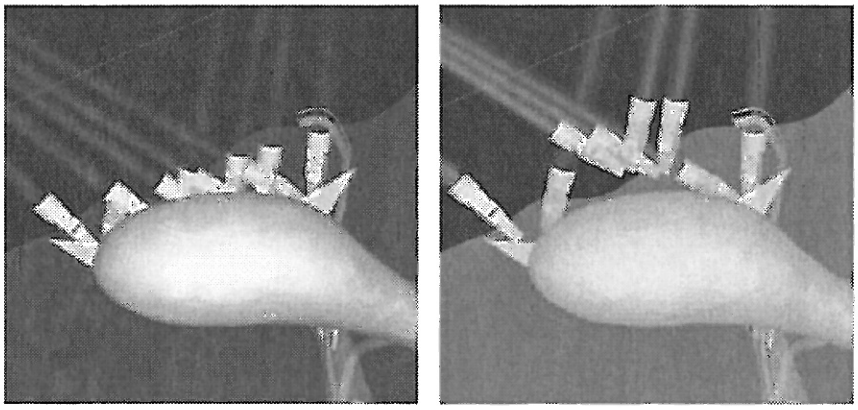
1. Generation of a valid, collision free path between the different targets.
2. Obtaining the pose of the robot that would allow such a path.

Here it should be noted that the proposed analysis is tailored to MIS robots having a number n_a of active dofs, and n_p of passive dofs, generally related to each other by a remote center mechanism. Therefore finding the pose of the robot corresponds to finding the value of the passive dofs (including the spatial positioning of the robot with respect to the patient) that allows the active joints to safely perform the surgical procedure.

Path Planning

Assume at this stage that the instruments have been introduced through appropriate ports into the desired cavity of the patient. To demonstrate the feasibility of the intervention, one can proceed by rehearsing the expected gross movements of the surgeon between the different targets he had defined, and check for collisions between the arms, with the patient or other structures, and for out of reach positions. This trajectory can be defined as a straight line between the targets; however, this might not be a realistic assumption when the targets are distant from each others. A better solution would be to follow the surface of the organ at a given distance, thus adapting to its form. This can be achieved by defining a scalar field that would be positive inside the surface of the organ, and negative outside, with increasing absolute values as we move away from the surface. The goal would then be to follow a level curve between the two targets. This is achieved by attracting the tool tip in the direction of the goal target, and applying a corrective motion proportional to the difference between the actual and desired values of the scalar field in the direction of the gradient of the field. Of course this is a local method where the different parameters have to be carefully tuned to insure a good motion of the tool tip.

The chosen scalar field is computed at any given point from the weights of the natural neighbors of that point divided by the distance between them (see [12] for more details). Information about the normals at the surface points can also be used. The obtained scalar field is defined everywhere within the convex hull, and is smooth except at the sample points. This technique relies on second order Voronoï diagram, and thus requires a Delaunay mesh of the sample points; however, it does not require an explicit surface of the organ, which can be a valuable advantage if the organ is not reconstructed (e.g. direct volume rendering is used for visualization).



Pose Planning

Definition: Pose planning is the problem of positioning a robot composed of active and passive joints, so as to achieve a collision free path along a given trajectory $g(t)$, possibly under additional spatial constraints c. Spatial constraints are static position or orientation values that have to be fulfilled by both passive and active joints.

Example of the daVinci system [2]: The daVinci system is used to perform a minimally invasive surgical procedure using two manipulator arms to carry the surgical instruments, and a third one to carry the endoscope. All three are introduced into the patient's body through stationary ports, which correspond to mechanically fixed points on each manipulator, called remote centers. Setting aside the distal articulations used for very small surgical movements, the tool arms can be described as having n_p stationary dofs and n_a active dofs. The goal is to find a configuration for the passive joints that would allow the active joints to follow a collision free path through a pre-determined set of points, while passing through the corresponding fixed remote centers. The path is found independently of the robot by following a level set around the concerned anatomical entity between the targets points set out by the surgeon, as described earlier. Moreover, the robotic arms are carried by a base that can move in the operating room; i.e., with 3 dofs.

It should be noted that this is a critical application; therefore, the correctness and completeness of the solution is required. Moreover, it may be desirable not only to find a collision free placement of the robot, but also to maximize the minimum separation between the manipulator arms and to provide safety margins, as the result of the planning might not always be perfectly reproduced under operating conditions.

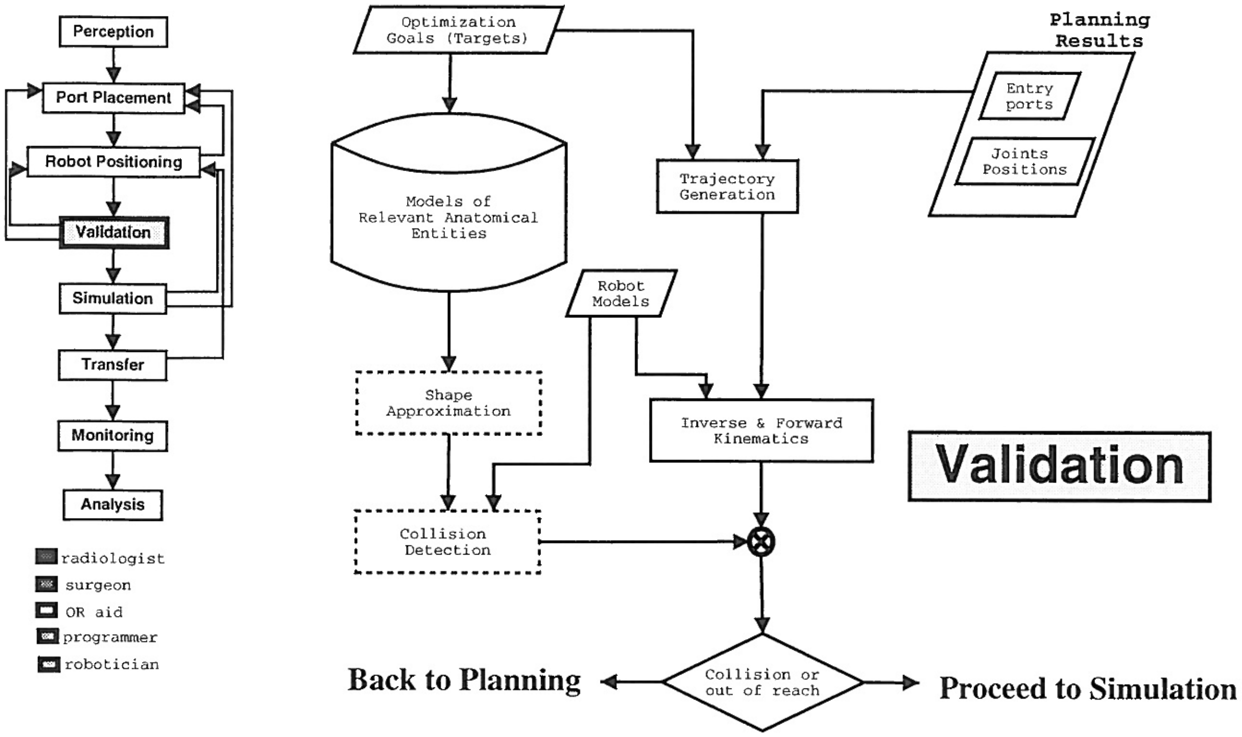
Solution for the daVinci system : The problem of following a path $g(t)$ under constraints c is formulated as an optimization problem of some objective function F representing the quality of the task

$$\begin{array}{cc} \min & F\left(x_{pose}\right) \\ x_{pose} \in \mathbb{R}^{n_{pose}} & \\ c\left(x_c\right) = 0 & \\ g\left(x(t)\right) = 0 & \end{array}$$

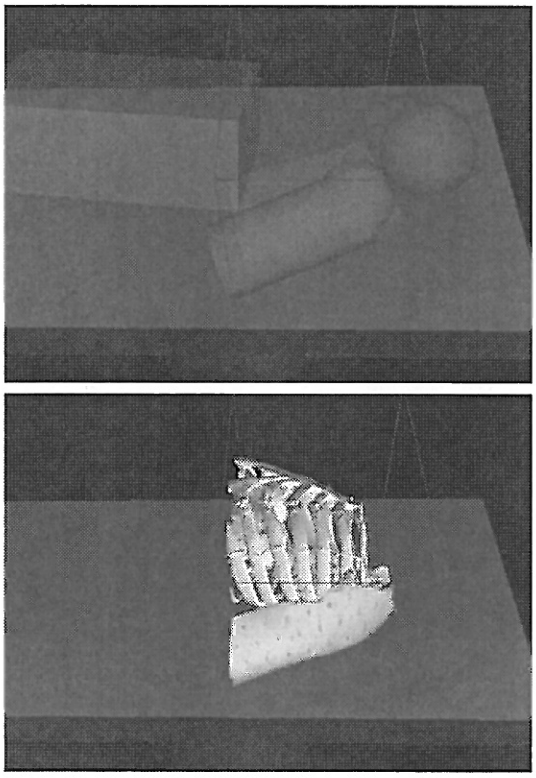
where for the daVinci system a suitable decoupled representation $x \in \mathbb{R}^{n_{pose}}$ is used, such that the constraints c (remote centers) can be satisfied by the n_c passive dofs while $g(t)$ can be followed with n_t active dofs. Then n_{pose} dofs are left for the pose (roll pitch yaw of the set-up joints + position of the base in the OR). $n_c + n_t + n_{pose}$ is the total number of dofs of the robot for the tool arms. The endoscope arm is not optimized although it is used in the evaluation of F. For a given pose x_{pose}, $F\left(x_{pose}\right)$ is equal to the minimum separation between critical parts of the robot, the patient (simplified geometry) and the OR settings while following the trajectory $g\left(t\right)$ that goes through the targets.

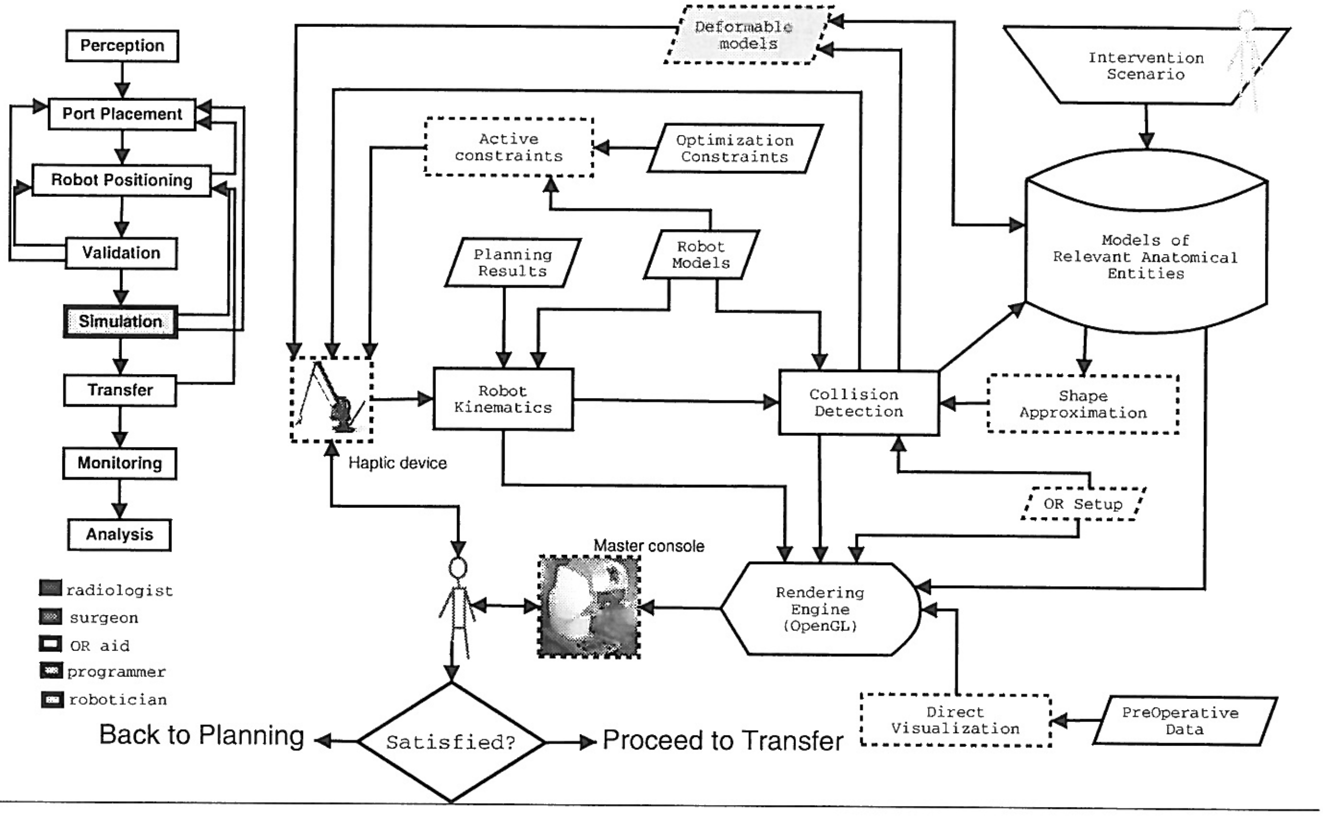
At this stage the positioning problem has become an optimization problem of a smooth function in $\mathbb{R}^{n_{pose}}$. An optimal solution is found using a *probabilistic gradient descend algorithm* (P-GD) coupled to a *feasible quadratic programming algorithm* (FQP), which is a super-linear convergence algorithm well suited to smooth multiple competing nonlinear objective functions under non-linear equality constraints. The P-GD algorithm is needed to find an initial solution that satisfies the equality constraints, from which the FQP algorithm will find an optimal solution by restricting its search in the feasible region of the search space. The correctness of the solution can be directly verified, and it can be shown to be probabilistically complete.

VALIDATION

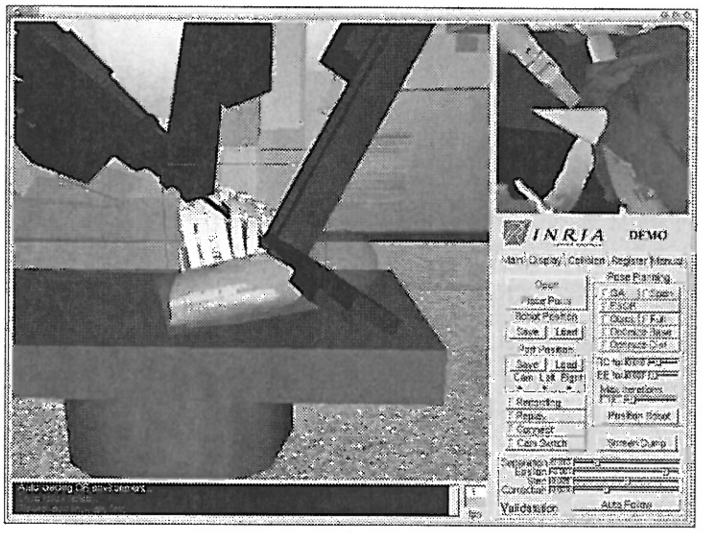


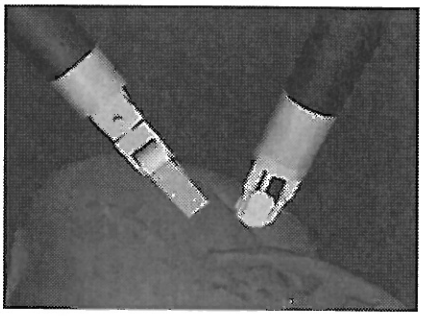
Generally, the validation step has no effect on the planning results, since the trajectory relating the target points had already been verified in the robot positioning step. Nevertheless, it may sometimes be too tedious to incorporate all possible constraints in the planning phase (e.g. details of patient anatomy), in which case some will be left to the validation phase, where a trial and error approach is used to find the best solution.



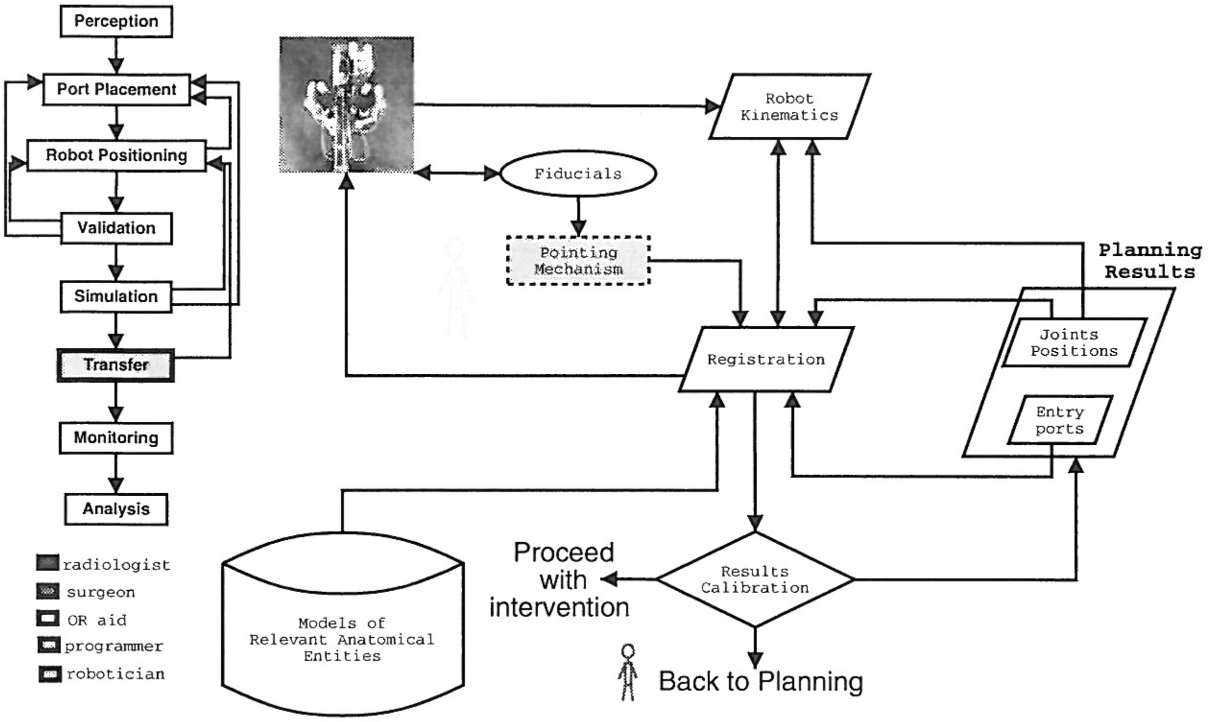


Simulation offers the surgeon a realistic environment to develop good control over the robot, in addition to getting accustomed to the intervention (training) and to the anatomy of the patient. It also plays an important role in the verification and validation of the planning results, since the direct manipulation of the robot by the surgeon could reveal complications not found in the automatic planning process. The simulation can be performed using specialized 3d pointing devices (with or without force feedback), or using the master console of the robot if technically possible.



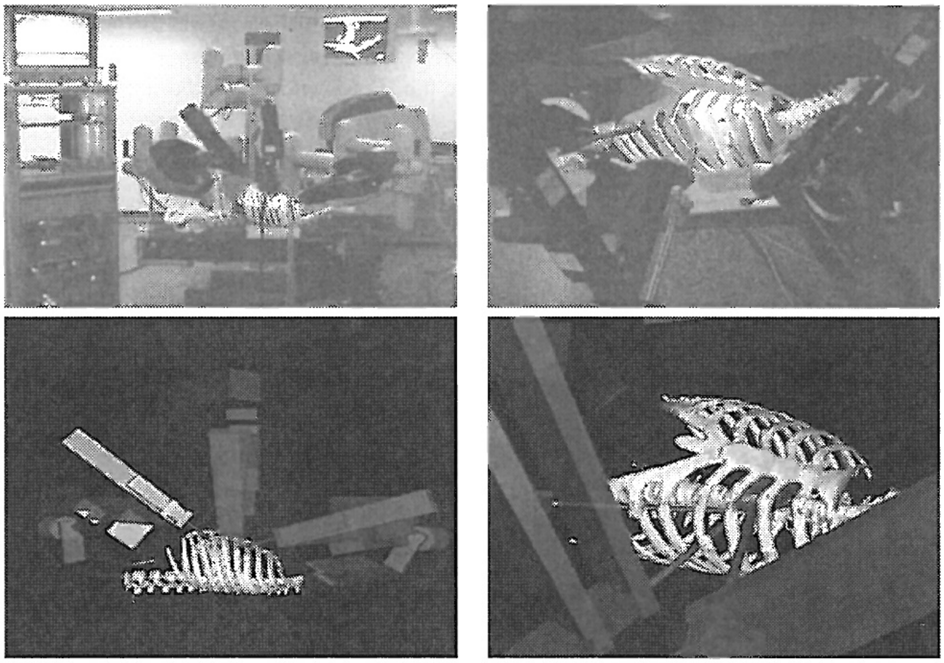


Another interesting aspect of the simulation is that it provides a safe and inexpensive platform for experimenting new robotic designs and new procedures.

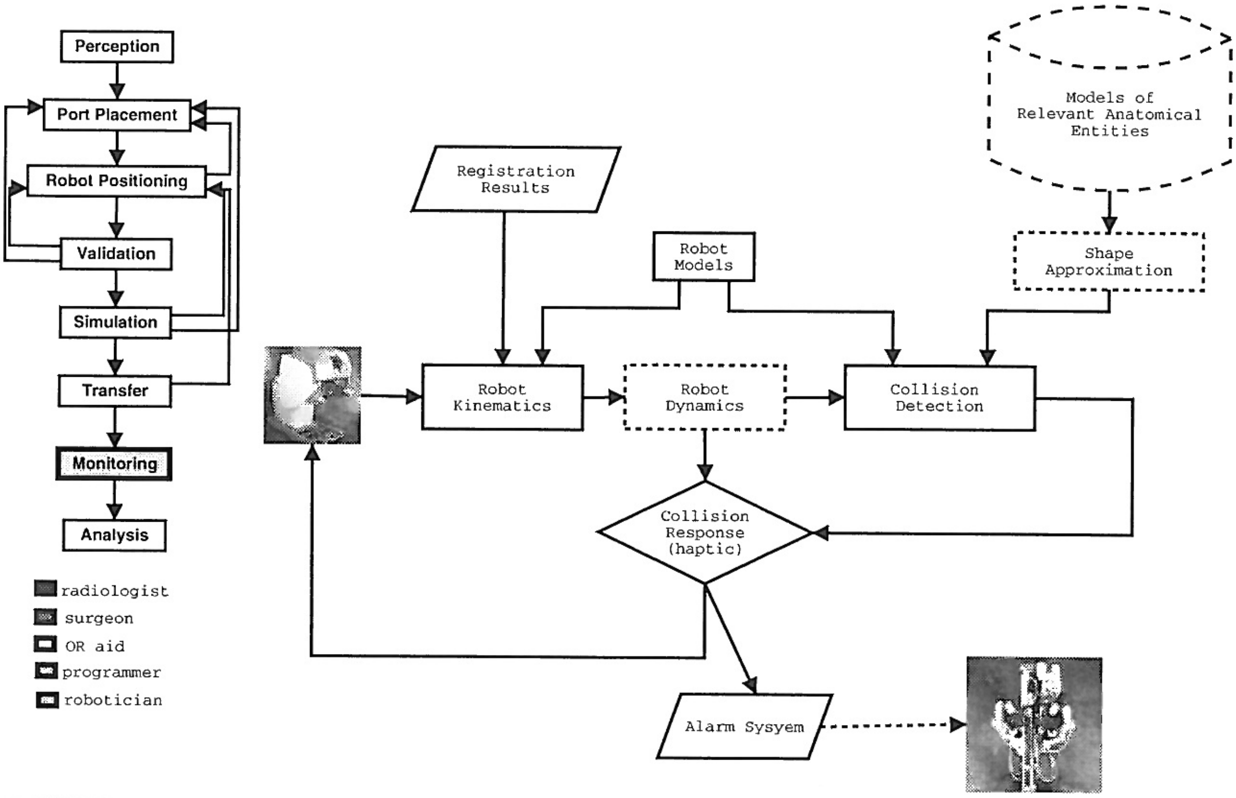


The positioning of the robot according to the planned results is achieved as follows:

1. Register the patient to the pre-operative data on which the planning had been carried out.
2. Recompute the port placement by taking into account the new position information.
3. Register the patient to the robot.
4. Position the robot according to the planned results.
5. Validate the positioning of the robot by automatically reproducing the expected surgeons' movements, and redo the planning if a problem is detected.



MONITORING



The monitoring of the intervention can be used as a safety trigger for collisions, instead of waiting for one to happen or constantly watching the robot as it comes close to a colliding state. In addition, distant monitoring can be used to overview the goings of the intervention. While distant control is not yet a feasible option, other communication channels can be used to change the course of the intervention.

CONCLUSION AND PERSPECTIVES

The proposed system is being implemented in INRIA Sophia-Antipolis with the daVinci [2] robot from Intuitive Surgical, and in cooperation with Prof. Alain Carpentier's heart surgery team in the Hôpital Européen Georges Pompidou. Experiments on a plastic phantom have produced satisfactory results for the planning and simulation steps (see [13]). The registration modality is being finalized in cooperation with the Intuitive Surgical team who is providing the appropriate APIs to connect to the robot. In the near future, a monitoring experiment will be carried out between the HEGP which is in Paris and INRIA Sophia-Antipolis (south of France) through a dedicated 2.5 Gbits/s network. The analysis step will be defined as soon as enough experiments are performed to give a basis for comparison.