# Optimized Port Placement for the Totally Endoscopic Coronary Artery Bypass Grafting using the da Vinci Robotic System*

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**Abstract.** This work presents the first experimental results of an ongoing cooperation between medical, robotics and computer science teams aimed at optimizing the use of robotic systems in minimally invasive surgical interventions. The targeted intervention is the totally endoscopic coronary artery bypass graft (TECAB), performed using the daVinci$^{\text{TM}}$ system (by Intuitive Surgical, Inc.). An integrated and formalized planning and simulation tool for medical robotics is proposed, and experimental validation results on an artificial skeleton and heart are presented.

## 1 Introduction

The introduction of robots in cardio-vascular surgery came from the limitations imposed on the surgeon by manually controlled minimally invasive surgery (MIS) instruments. Namely, the surgeon finds his movements, vision and tactile sensing reduced and severely altered [8, 3]. The use of a robotic manipulator can remedy the loss of dexterity by incorporating additional degrees of freedom at the end of the tools, as is the case with the EndoWrist$^{\text{TM}}$ movement of the daVinci$^{\text{TM}}$ system (see [4] for details about the system). In addition, a robotic system offers an increased precision and stability of the movement.

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. Therefore these sites have to be carefully chosen for each patient, depending on his anatomy and the requirements of the intervention. 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 *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 with the

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manipulator arms. Again this stresses on 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. The simulation can also be very useful as an educational tool.

Experiment driven guidelines for optimal port placement had already been proposed by leading surgeons in the field (e.g. [8]); however, it should be clear that the above enumerated criteria cannot be mentally pictured and taken into consideration for each patient. Such a quantity of high precision information cannot be handled by the surgeon alone. A computerized approach offers an efficient fusion of the anatomical data of the patient, the robot characteristics and the requirements set out by the surgeon, by translating the aforementioned into mathematical criteria suitable for optimization. This can be done through an integrated planning and simulation interactive system presented in this paper.

## 2 General Approach

We propose an integrated approach in which all the processing and user interaction are lumped in a single interface 1, schematically summarized in figure 2.

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 guarantee their feasibility. We also simulate the intervention in real-time, paying particular attention to potential collisions between the robotic arms. This paper focuses on the planning and experimental testing steps. Details about the rest of the steps can be found in [1].

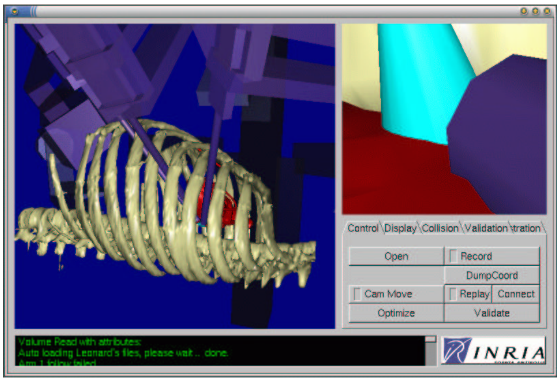

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**Fig. 1.** The planning and simulation interface.

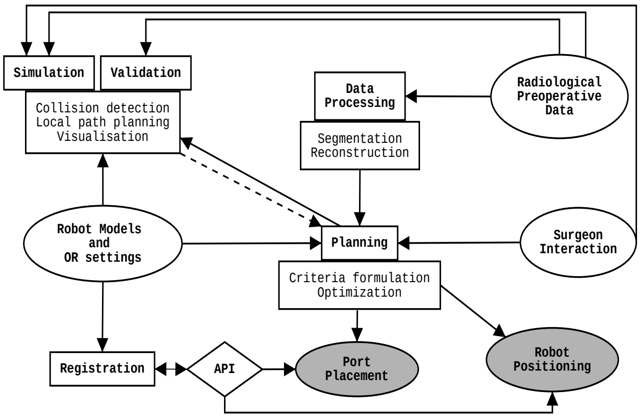


**Fig. 2.** A modular view of the overall approach.

# 3 Planning

The planning step can further be broken down into:

1. Finding an optimal triplet for the incision sites.
2. Finding an adequate positioning of the robot.

A two step approach simplifies considerably the problem, and enables a better distinction between the limitations imposed by the minimal invasive access, and those imposed by the robot. Clearly, the two steps are not totally independent, as will be seen in the rest of this section.

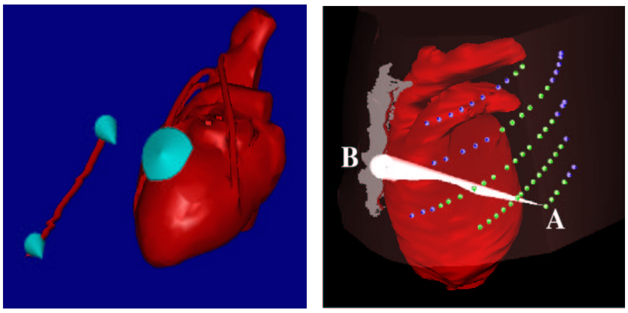
## 3.1 Triplet Optimization

After having identified a set of points that can be used for the access of the robotic tools (the intercostal spaces as explained in [1], see 3 (b) ), referred to as admissible points, an exhaustive search for a triplet that insures the best accessibility of the tools is carried out. Moreover, other requirements have to be present such as a “comfortable” position for the surgeon, in addition to some anticipation for the robot positioning step.

*Targets:* Target points represent the area on which the surgeon would work, and the direction along which he would be able to achieve his task, which is dictated by the physiological of the patient. A typical example is shown in figure 3 (a).

*Criteria:* Each admissible point goes through a series of tests to characterize its adequacy for use as an entry point for the robotic tool or the endoscope. There are qualitative and quantitative tests as described next:

Qualitative tests concern the reachability from an admissible point to the target areas, where the point is eliminated if any of the following conditions holds:



(a) Targets (b) Reachability test

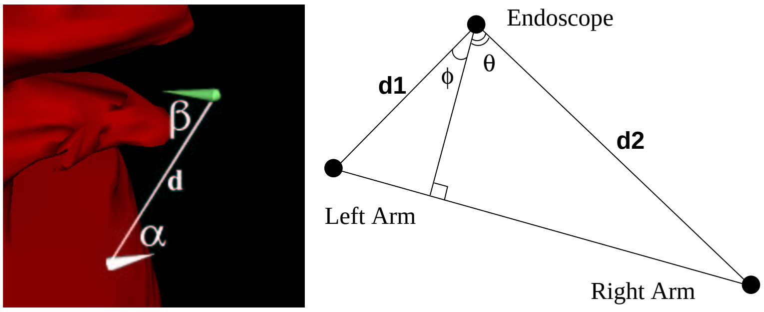
**Fig. 3.** Targets and collision test (see text).

- The length of the tool between target and admissible is outside a given range, which simply means that the area cannot be operated using the concerned instrument. ($d$ in figure 4 (a), not used for endoscope)
- The angle between the admissible direction and the line relating the target to the admissible is too big, in which case the tool may damage the adjacent ribs ($\beta$ in figure 4 (a)).
- The path between the admissible point and the target area is not clear; i.e., it is hindered by an anatomical structure as is shown for instance in figure 3 (b). The graphics hardware is used to perform this test in a way similar to the work described in [7].

Quantitative tests concern the dexterity of the robot, where each admissible point is graded based on the angle between the target direction and the line relating the target to the admissible ($\alpha$ in figure 4 (a)). This measure translates the ease with which the surgeon will be able to operate the concerned target areas from a given port in the case of a robotic tool, or the quality of viewing these areas for an endoscope.

*Optimization:* Finding the best triplet of ports is done in two steps: First the best endoscope position is chosen based on the above listed criteria, then all possible pairs are ranked according to their combined quantitative grade and their position with respect to the endoscope. More precisely, the triplet is ranked in a way that insures a symmetry of the left and right arms with respect of the endoscope, and favors positions further away from the endoscope to give a clear field of view (formally this corresponds to maximizing $\phi$ and $\theta$ defined in figure 4). Moreover, and in order to anticipate on the next step which is the robot positioning, port that are too close are not considered in the optimization, as they would most certainly result in a colliding state.

This optimization is exhaustive; 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 are performed.



(a) (b)

**Fig. 4.** Parameter definition for triplet optimization (see text).

### 3.2 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. The following section describes the problem in more detail and discusses the proposed solution.

*Problem Description* The positioning problem consists of finding an initial pose of the robot with respect to the patient, such that **all targets** are reachable without violating any of the constraint enumerated in the next section. In addition, the robot can have degrees of freedom (dofs) that are not teleoperated (passive), and that serve for the set-up of the active joints (see 4.1 for the case of the daVinci$^{\mathrm{TM}}$ robot which increases the total number available dofs to 34).

*Constraints:* The following list captures the constraints imposed upon the robot.

1. Ports: 9 dofs corresponding to 3 positions in space
2. Collisions between the robot arms
3. Collisions between an arm and the patient (e.g. shoulder)
4. Other collisions (e.g. with anesthesia equipment or OR table)
5. Miscellaneous constraints (e.g. endoscope orientation for assistant surgeon)

Certain constraints are more difficult to express than others, especially when it comes to subjective measures such as the preferences of the surgeon or the settings of the OR. In addition, not all constraints can always be expressed; for instance, if the CT scan does not incorporate the shoulder, then the corresponding collision constraint cannot be formulated.

*Solution* Although impressive theoretical and practical results can be found in the literature on the solution of path planning problems solved both in the robot articular [5, 9] and cartesian space [6, 2], it should be understood that this is not a path planning problem in two respects:

First the start and goal points are not defined, since there are infinitely many solutions to place the robot over the desired ports. In terms of the robot articular space, this means that there are a start subspace and a goal subspace that can have dimensions as high as half the dimension of the articular space.

Then we should keep in mind that even if, for instance, a path is identified to go from one position to another given a certain configuration, then this path may be too complex for the surgeon who will be teleoperating the robot to reproduce. In other words, there is no point in planning in the articular space of the active joints, which leaves us with passive joints that in turn are supposed to stay stationary during the intervention.

A potential field method on the passive joints would be a natural solution for such a problem; however, formulating a good field with the above constraints does not seem to be feasible.

At the present time we use a combined probabilistic and gradient descent approach, in which configurations of the passive joints (including a translation of the base) are randomly drawn in robot articular space. To each configuration, a cost function is associated that depends on the above enumerated constraints. These configurations are then used to get new ones, for which a low cost function gives its corresponding configuration a high selection probability. This process is repeated until convergence to a cost function that is less than a given tolerance.

Clearly, the formulation of the constraints plays a key role in the solution. For a given configuration, the cost function is infinite if a collision is detected, else it is inversely proportional to the distance from the desired port. Moreover, and once the cost function is low enough (i.e., the passive joints are close enough to the desired port), the active joints are moved over all the targets (using inverse kinematics), and collisions are checked.

The main advantage of this method is its flexibility in formulating constraints. For instance, we can easily favor a low opening of the left passive joints in order to avoid conflicts with the anesthesia equipments, by giving these joints a positive effect in the cost function. However, much tuning is required in setting the cost function and the different parameters, which may make the use of such an approach tedious. A more systematic method based on a local planning method is being prepared and will be presented in future works.

## 4 Experimentation and Results

The validation of the approach is carried out on a plastic skeleton and heart that were CT scanned, and on which the usual pre-processing, planning, validation and simulation steps were performed. The results obtained, as well as the registration and the "clinical" assessment of the positioning, is presented in this section.

### 4.1 Experimental Setup

*The TECAB intervention:* The TECAB intervention consists of grafting on a damaged coronary artery, such as the left anterior descending (LAD), another artery (typically the left internal mammary artery or LIMA) that would be used as a bypass to irrigate the affected portion of the heart. The entire intervention is performed through incisions in the chest, where carbon dioxide is insufflated to collapse the left lung, thus enabling the movement of the instruments.

*OR Setup:* The setup is shown in figure 5, where a plastic skeleton and a heart fixed inside it are used. Moreover, two radio opaque metal strips were used inside the skeleton to represent the LIMA and LAD.

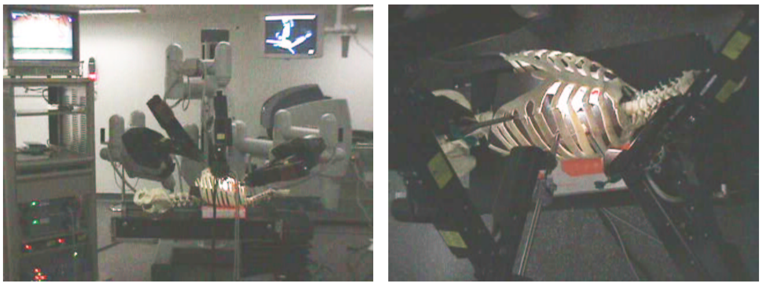


**Fig. 5.** Experimental setup, the simulation view can be seen on the top right corner of the left image.

*The daVinci*$^{\mathrm{TM}}$ *System and API:* The daVinci$^{\mathrm{TM}}$system is a teleoperated robot composed of two arms to hold the surgical tools and a third to hold the endoscope, all mounted in the same base. Each arm comprises an active (4 dofs) and a passive part (6 dofs for a tool arms, and 4 for the endoscope arm). In addition, the tool arms incorporate an active end effector that has 3 dofs and a gripper. The passive joints, referred to as set-up joints, are used to position the remote center (fixed point) of the active joints on the ports before the intervention begins. More details about the system can be found in [4].

The API connects a client software to the robot, enabling a real-time reading of the active joints, and a cartesian position of the remote centers with respect to the base of the robot.

### 4.2 Planning results

The optimized port placement and robot positioning are shown in figure 6, which are the result of the targets shown in 3 (a). Referring to 3.2, only the first two constraints where incorporated in the planning. These may be described as being on the 3rd and 5th intercostal space below the anterior auxiliary line, and on the 7th at the cartilage limit for the left, endoscope and right arm respectively.

### 4.3 Registration

The positioning of the robot according to the planned results is achieved in two steps: first register the robot to the skeleton, then place the port. This is a preliminary method used as a first attempt to quantify the difficulty of the registration, and should not be considered as a standard approach.

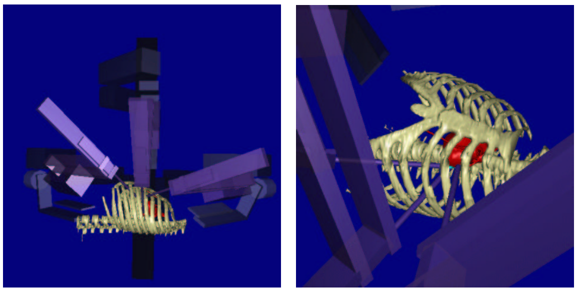


**Fig. 6.** The planned positioning and port placement.

*Patient-Robot* The pose of the robot with respect to the skeleton is subject to 6 dofs (3 translations and 3 orientations). The rotational dofs are not registered because we assume that the robot base will be parallel to the OR table, and that the relative tilt between the skeleton and the OR table is the same as the one in the CT scan. The translational pose is registered by pointing an easily identified point (the tip of the sternum) *in the simulator* using the endoscope arm, and reading the corresponding articular values. Then robot base and its first translational joint (up/down) are moved so that the articular values read through the API match the computed ones. This was done manually with a positioning error of $1.5^o$.

*Ports* Once the robot is registered to the skeleton, positioning the ports can simply be achieved by moving the robot arms according to the precomputed articular values that correspond to having the remote center on the port. On the other hand, the results of the planning can also be expressed as a quantitative description of the positions of the port; e.g., endoscope arm at 3rd intercostal space at the limit of the cartilage. This is a relatively accurate description since the port are known to be in the intercostal spacing; therefore, only 1 dof (inside the spacing) remains to be set, which is easily achieved since the skeleton has many metal fiducials used to bind it together.

This placement method was successfully carried out on the endoscope arm with a relative error in the positioning of $0.6^o$, and an absolute error in the port location of 22 mm. However, positioning the 6 dofs setup joints was not possible by manually moving every articulation. Therefore, the quantitative description was used to place the ports. In other words, a 6 dofs arm is positioned using a 3 dofs constraint. The errors on the joint values was very high as expected (more than $85^o$); however, the absolute port position error was 12 mm.

### 4.4 Clinical Assessments

Although the registration step is not yet satisfactory, the clinical assessment of the positioning turned out to be very encouraging are described next.

*Reachability and Dexterity* The steps of the TECAB intervention were performed on the skeleton, and the surgeon described the configuration as very satisfactory in terms of reach and the available dexterity at the tool tips.

*Collisions* No collisions occurred between the arms during the entire "intervention". However, it should be noted that the robot arm would have been in conflict with the shoulder and the diaphragm of the skeleton, which means that these constraints would most probably have had a big impact on the port placement. These will be included in the next set of tests by adding a shoulder and diaphragm to the skeleton.

### 4.5 Comparison with Clinical Solution

The positioning problem of the robot is largely due to the non-invasive nature of the intervention. More precisely, the surgeon has two major problems to face: he does not have an accurate idea about the location of the areas he wants to operate on with respect to the patient's chest, and he cannot try out different port configurations to avoid collisions with the robot. In the case of the plastic phantom; however, all the anatomical entities are visible from the outside, and there is no harm in re-positioning the ports according to the needs of the intervention. Therefore, and given enough time, a conventional port placement on a plastic skeleton can be used as a gold standard for the proposed automatic port placement.

In terms of anatomical landmarks, the two results differ in the endoscope position which is one rib higher, and in the right arm position which is one rib lower and closer to the sternum. The similarity between the results is encouraging, especially if we keep in mind that the clinical solution was driven by experience on real patients; therefore, for instance, the surgeon would not use the 7th intercostal space for the right arm (as proposed by the automatic planning), since it may be too close to the diaphragm.

Alternatively, we believe the proposed planning will ultimately change the way the clinical procedure is performed, were the final verdict will be given by the goings of the intervention. Finally, comparing the robot positioning does not yield any useful information, since both positions were collision free.

### 4.6 Recording

An additional useful feature of the system is that the entire intervention can be recorded and played back at a later time, or at a remote location. This was done successfully; however, the replay in simulation was difficult to assess since registration errors were too large, thus the reproduced gestures did not correspond to the clinical ones.

### 4.7 Assessments

The results obtained indicate that the proposed approach can considerably simplify and improve the positioning of the robot on the patient. The registration remains the weak chain in the process, although its effects can be minimized when complemented with anatomical landmarks for the port locations.

Potential problems due to an incomplete modeling of the plastic phantom and the OR settings were identified, these should be incorporated into future experimentations.

## 5 Conclusion

An integrated planning and simulation system for minimal invasive robotically assisted surgery was presented, along with a preliminary registration method. The approach was validated on a plastic phantom, and preliminary results were very encouraging. We believe that this approach is poised to bring significant advanced in the way robot will be used in the operating room. In addition to being a useful visualization and simulation tool, it opens new possibilities for testing prototype robotic tools and unconventional interventions in simulation.

Future efforts will be directed towards more validation of the approach, and improving the robot positioning algorithm and the registration process.

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