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Preoperative Planning of Robotics-assisted Minimally Invasive Coronary Artery Bypass Grafting

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Abstract— **This paper outlines a framework for the preoperative planning of robotics-assisted minimally invasive cardiac surgery with application to coronary artery bypass grafting. The intent of the proposed framework is to improve surgical outcomes by considering the intraoperative requirements of the robotic manipulators and the anatomical geometry of the patient's chest. This includes target reachability, instrument dexterity for critical surgical tasks and collision avoidance. Given the patient's preoperative chest computed tomography images, the planning framework aims to determine the optimal location of the access ports on the ribcage, along with the optimal pose of the robotic arms relative to the patient's anatomy. The proposed multi-objective optimality criteria consist of a measure of clearance as well as a new collective kinematic measure. The minimum distances among the robot arms provides a measure for the likelihood of collisions. The proposed kinematic measure is composed of two modified manipulability indices that are dimensionally homogeneous and, in contrast to previously-used measures, are more likely to yield isotropic force and torque distributions when optimized for surgical interventions. The results of a case study illustrate the compatibility of the framework with general guidelines used by experienced surgeons for port selection. Furthermore, the framework surpasses those guidelines by ensuring the feasibility of the solutions in the sense of collision avoidance and surgical target reachability.**

I. Introduction

Minimally Invasive Cardiac Surgery (MICS) was originally introduced to reduce the invasiveness of Open Cardiac Surgery (OCS). MICS uses laparoscopic surgical instruments and an endoscope that enter the chest cavity through small incisions in the chest wall. Despite many benefits, this technique has drawbacks that arise from the restricted access through the incisions, which create a Remote Center of Motion (RCM). The RCM is the pivot point of the surgical instrument at the entry port that constrains the degrees of freedom available in the chest cavity. Reduced reachability and dexterity, poor, visual perception, collisions and sight occlusion, tool/hand motion reversal and force attenuation are among the disadvantages of minimally invasive surgery.

Coronary Artery Bypass Grafting (CABG) is a cardiovascular treatment with promising clinical outcomes. The procedure involves harvesting the Left Internal Mammary Artery (LIMA), on the chest wall, from the first to the sixth intercostal space and performing an anastomosis between the harvested LIMA and the Left Anterior Descending (LAD) artery, located on the anterior surface of the heart, in order to bypass a blockage [1]. Due to the difficulties in reaching and dissecting the distal and proximal endpoints of the LIMA, LAD exposure and anastomosis, minimally invasive CABG had limited popularity when first introduced. Robotically-Assisted Minimally Invasive Cardiac Surgery (RAMICS) addressed these shortcomings by providing additional dexterity and enhanced reachability of surgical targets. However, research suggests that clinical outcomes could be further enhanced by a preoperative planning procedure that takes the robotic aspects of the surgery into account.

Optimal port placement within the patient's intercostal spaces is a vital aspect of surgical planning that has direct impact on the outcomes of RAMICS. Poor port selection and/or poor positioning of the robot may lead to an increased chance of collisions, to reduced manipulability and ultimately to port repositioning or even conversion to OCS. Currently, experienced surgeons select the port locatios using external anatomical features. In most cases, this process is performed to enhance surgical target reachability and does not adequately address the kinematic aspects of RAMICS, such as robot pose planning. This suggests that a novice surgeon may get results that are inferior to those obtained by an experienced RAMICS surgeon.

Research on optimal planning of RAMICS has been initiated recently. As a pioneering work for preoperative port planning, a system for 3D visualization of intrathoracic models constructed from preoperative Computed Tomography (CT) and Magnetic Resonance Imaging (MRI) was described in [2]. In [3], results of a feasibility study on

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planning for the *da Vinci*® surgical system, were reported. The focus of this study was to examine the robot's *Global Conditioning Index* (GCI) for a number of candidate port positions to ensure the highest manipulability within the surgical workspace. The results showed a potential performance increase of up to 29% in comparison with ports selected by an expert surgeon. An optimal port placement for CABG using preoperative patient data was accomplished in [5]. It was claimed that the proposed performance criteria were insensitive to intraoperative perturbations. The authors reported up to 43% improvement in the dissection time. The most comprehensive planning strategy for the *da Vinci* system so far has been reported in [6]. The authors proposed a two-fold planning strategy, including optimal port planning and optimal robot pose planning to enhance dexterity and visibility of an intraoperative collision-free operation.

This paper outlines the development and validation of a planning framework for RAMICS, based on patient-specific anatomical models. The goal of this framework is to assist a novice surgeon in the preoperative planning of robotically-assisted CABG, enabling him or her to obtain results that are equivalent to the results obtained by an experienced surgeon.

The layout of the rest of the paper is as follows: in Section II, a description of the kinematics of the *da Vinci* surgical manipulator is presented. Section III outlines a modified kinematic measure for surgical applications. Section IV addresses the collision avoidance problem and the development of the measure of clearance. In Section V, the formulation of the planning strategy into an optimization problem is discussed. The results of a case study are reported in Section VI. Finally, concluding remarks and future work are discussed in Section VII.

II. The *da Vinci* Surgical Manipulator

The *da Vinci* surgical system (Intuitive Surgical, Inc., Sunnyvale, CA) is currently the only approved tele-manipulation platform being utilized for RAMICS worldwide. The complete platform consists of two subsystems: the surgeon's console and the multi-arm robotic system. The console is designed to deliver an efficient and reliable tele-manipulation experience for the surgeon.

The patient-side sub-system has four mechanical arms consisting of three instrument arms and an endoscopic arm. Only two of the instrument arms are active at one time (referred to as left and right). Each instrument arm possesses six passive joints, and a double parallelogram with three active joints that act as a spherical joint. Three additional Degrees Of Freedom (DOFs) are provided by the active joints of the tool, attached to the arm. During an operation, the RCM of the spherical mechanism is positioned at the port of entry to avoid exerting excessive forces at the incision point.

Fig. 1 illustrates the active section and the relevant attached frames. The base frame is chosen to be attached at the RCM (port of entry), which will simplify further kinematic analyses. By utilizing the convention outlined in [7] and the frame positioning illustrated in Fig. 1, Denavit-Hartenberg (DH) parameters were calculated, as shown in Table I.

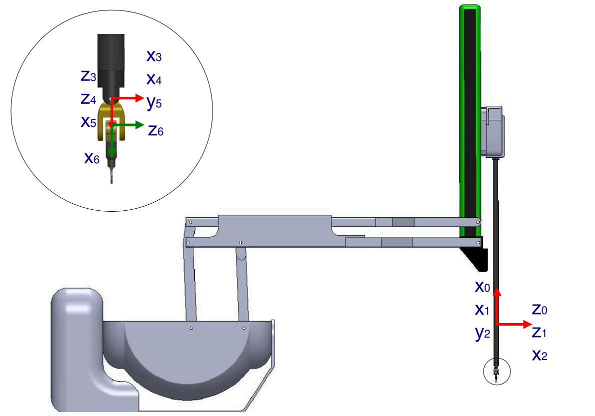

Fig. 1. Assigned frames on active arm section of *da Vinci* manipulator.

TABLE I
DH Parameters of *da Vinci* Active Sections

Joint	θ	d	a	α
1	θ_1	0	0	0
2	θ_2	0	0	$-\frac{\pi}{2}$
3	0	d_3	0	$\frac{\pi}{2}$
4	θ_4	0	0	0
5	θ_5	0	0	$-\frac{\pi}{2}$
6	θ_6	0	a_6	$-\frac{\pi}{2}$

III. Kinematic Manipulability

Kinematic performance measures for robotic manipulators have been studied extensively in the last two decades. *Manipulability*, *dexterity*, *isotropy* and *transmissibility* are the most popular robot performance measures. While conceptually related, none of these measures can be fully associated with a physical attribute of a mechanism.

The volume of the *manipulability ellipsoid* was proposed in [8], as a measure of uniformity of the mapping between joint space and task space and as a measure of proximity to the singular configuration. In [9], the Jacobian singular value was proposed as a measure of isotropy. In an isotropic configuration, by definition, all the singular values of the Jacobian matrix are equal and nonzero. The GCI, as a modified measure of isotropy, was recommended for mechanism design in [4]. A class of kinematic performance measures was developed in [10] by associating two Riemannian metrics in task space and joint space. However, the authors showed that there was no natural choice of metrics in task space, resulting in a somewhat arbitrary measure.

In fact, none of the aforementioned performance measures meet the essential objectivity requirements: frame invariance and/or dimensional inhomogeneity. While the former has been resolved to some extent in most of the recently proposed measures, the latter remains a problem. It was suggested in [11] that use of a characteristic length gives a dimensionally homogeneous Jacobian matrix, and in [12] pre- and post- multiplication of the Jacobian matrix by the maximum available torque and force scaling matrices was proposed. However, none of these methods have been entirely justified to give objective kinematic measures. One or more of the above-mentioned measures have been utilized in [3], [13] and [12] to evaluate the performance of the robots in surgical applications.

In this section, an extension of the measure of isotropy given in [4], is proposed to quantify the performance of the robot for surgical interventions. The proposed measure is dimensionally homogeneous, in contrast to the original GCI. The essence of this measure comes from the surgical task motion analysis reported in [14]. According to their results, most surgical tasks such as suturing and knot tying could be decomposed into a sequence of simpler tasks involving fixed-position or fixed-orientation motions.

Two constrained variants of the Frobenius condition number, the fixed-position, κ_{fp}, and the fixed-orientation, κ_{fo}, condition numbers may be defined as:

$$\kappa_{\mathrm{fp}} = \sqrt{\mathrm{tr}(\mathbf{J}_{\mathrm{fp}}\mathbf{J}_{\mathrm{fp}}^T)\mathrm{tr}((\mathbf{J}_{\mathrm{fp}}\mathbf{J}_{\mathrm{fp}}^T)^{-1})}, \quad (1)$$

$$\kappa_{\mathrm{fo}} = \sqrt{\mathrm{tr}(\mathbf{J}_{\mathrm{fo}}\mathbf{J}_{\mathrm{fo}}^T)\mathrm{tr}((\mathbf{J}_{\mathrm{fo}}\mathbf{J}_{\mathrm{fo}}^T)^{-1})}, \quad (2)$$

where $\mathbf{J}_{\mathrm{fp}}$ and $\mathbf{J}_{\mathrm{fo}}$ are the fixed-position and the fixed-orientation Jacobian matrices, respectively. The *task priority* concept was used in [15] for derivation of an expression for the Jacobian of mechanisms operating subject to kinematic constraints. Following the same approach, expressions for the fixed-position and the fixed-orientation Jacobian matrices are given by:

$$\mathbf{J}_{\mathrm{fp}} = \mathbf{J}_{\omega}(\mathbf{I} - \mathbf{J}_{\mathrm{v}}^{+}\mathbf{J}_{\mathrm{v}}), \quad (3)$$

$$\mathbf{J}_{\mathrm{fo}} = \mathbf{J}_{\mathrm{v}}(\mathbf{I} - \mathbf{J}_{\omega}^{+}\mathbf{J}_{\omega}), \quad (4)$$

where $\mathbf{J} = \begin{bmatrix} \mathbf{J}_{\mathrm{v}} \\ \mathbf{J}_{\omega} \end{bmatrix}$ is the Jacobian of the mechanism and $\mathbf{J}_{\mathrm{v}}$ and $\mathbf{J}_{\omega}$ are the translational and rotational sub-matrices respectively. It is straightforward to justify that the restricted Jacobians are dimensionally homogeneous. Accordingly, the constrained versions of the GCI can be defined as:

$$M_{\mathrm{FPGCI}} = \frac{\int \kappa_{\mathrm{fp}} d\Pi}{\int d\Pi}, \quad (5)$$

$$M_{\mathrm{FOGCI}} = \frac{\int \kappa_{\mathrm{fo}} d\Pi}{\int d\Pi}, \quad (6)$$

where $d\Pi$ is the *volume form* of the manifold in which the index is calculated. Finally, a collective performance measure with application to surgical tasks should encompass both of the indices, given by:

$$M_{\mathrm{CGCI}} = \gamma_1 M_{\mathrm{FPGCI}} + \gamma_2 M_{\mathrm{FOGCI}}, \ 0 < \gamma_1, 0 < \gamma_2 \quad (7)$$

where γ_i are scaling factors for fine-tuning of the measure, and M_{CGCI} is the proposed Collective global Conditioning Index (CGCI).

IV. Collision Avoidance

Frequent collisions among the arms and the patient's anatomy during interventions may slow down the procedure and sometimes may result in conversion to OCS. Although, appropriate positioning of the *da Vinci* active sections relative to the patient's anatomy may not eliminate the risk of intra-operative collisions entirely, due to the uncertainties existing in human-in-the-loop tele-manipulation systems, it could still help to decrease the risk of collisions. This motivates the inclusion of collision avoidance into the planning strategy.

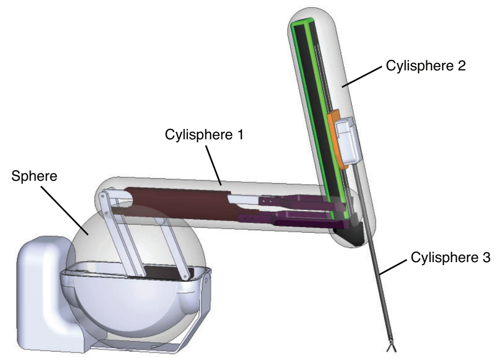

Fig. 2. The *da Vinci* active section is modeled by geometric primitives, three cylispheres and a sphere, to simplify distance calculations.

A. Body Geometric Modeling

The initial step toward collision-avoidance programming is the geometric modeling of the bodies using a set of geometric primitives. In this work, the *da Vinci* active section is modeled using *cylispheres* utilized in [16] and [17] for modeling robotic arms. Use of this primitive has been proven to be efficient for minimum distance calculations, since it is an extension of line segments. As Fig. 2 illustrates, the active section is decomposed into three cylispheres and a sphere. This primitive set results in fairly accurate, yet nonconservative collision detection.

B. Measure of Clearance

The minimum distance between the manipulators can be expressed in terms of distances between their primitives using the closed-form solutions given in [17] for cylisphere-cylisphere and cylisphere-sphere cases. This yields:

$$d_{\min} = \min_{i,j}\{d_{ij}\}, \quad (8)$$

where d_{ij} denotes the distance between ith primitive of the first arm and the jth primitive of the second one. This gives a fast and accurate way of evaluating the instantaneous minimum distances between the arms. Clearance may be defined as the infimum of these calculated minimum distances as the instruments reach individual target points during the operations; i.e.,

$$C(\mathbf{Q}_{\mathrm{r}}, \mathbf{Q}_{\mathrm{l}}, \{\mathbf{p}_{\mathrm{t}}(k)\}, \mathbf{p}_{\mathrm{b,r}}, \mathbf{p}_{\mathrm{b,l}}) = \inf_{k} d_{\min}(k), \ k = 1,2,..,N \quad (9)$$

where N is the number of sampled target points, the l and r indices are used to distinguish between the left and the right arms, and $\mathbf{p}_{\mathrm{b}}$ and $\mathbf{p}_{\mathrm{t}}$ are vectors denoting the position of the ports (which are assumed to coincide with the origin of the base frame) and the target, respectively. Accordingly, $\mathbf{Q}$ denotes the unit quaternion representation of the base frame orientation with respect to the world reference frame.

V. Optimization Formulation

This section outlines the formulation of the proposed surgical planning framework. The formulation will involve a constrained optimization that seeks the optimal position of the ports on the patient's rib-cage, along with the optimal orientation of the active section relative to the patient's geometry. In other words, the positions and the orientations of the left and the right active sections comprise the parameters of an optimization formulated as:

$$\min_{\mathbf{Q}_r,\mathbf{Q}_l,\mathbf{p}_{b,r},\mathbf{p}_{b,l}} U, \tag{10}$$

$$g_i \leq 0, \tag{11}$$

where U and g_i are the index function and the constraints respectively.

Since the InterCostal Spaces (ICS) form the potential admissible port positions, these loci can be represented by a set of parametric curves $\mathbf{p}_{b,r} \in \mathbf{c}_r(u_1)$, $\mathbf{p}_{b,l} \in \mathbf{c}_l(u_2)$ where $\{\mathbf{c}_r, \mathbf{c}_l\}$ is a set of spatial parametric curves with $0 \leq u_i \leq 1$ for $i = 1,2$. Finally, the curve parameters u_1, u_2 represent new optimization parameters, replacing their corresponding vectors $\mathbf{p}_{b,r}, \mathbf{p}_{b,l}$, respectively.

A. Objective Function

As discussed previously, the manipulability and clearance measures are intended to be incorporated into the objective function. It can be shown that both clearance and manipulability are dependent on the positions and orientations of the arms. This means that the optimization is not separable and a *Pareto* optimal solution should be sought by optimizing utility functions.

To further ensure the feasibility and acceptance of planning outcomes, surgeon's preferences should also be considered. The optimal tool approach angle with respect to the surgical target has been investigated in clinical studies such as [18], while some guidelines on optimal instrument angles in a surgical planning study have been considered in [5]. Both of these studies agree on the idea that an optimal manipulation angle, the angle between the instruments, is around 60°. According to the authors, this angle provides the maximum flexibility for interaction with the tissue and the other tool. Furthermore, the elevation angle, defined as the angle between the instrument and the horizontal plane, provides the surgeon with a wider range of approach angles during interventions [5]. The authors also recommended an angle of 45° at the anastomosis site and -20° for LIMA harvesting.

The above-mentioned optimality conditions, along with the proposed CGCI and measure of clearance, result in the following the objective function for a given surgical target:

$$U = \sum_i U_i, \tag{12}$$

where U_i are utility functions given by:

$$U_1 = w_1 M, \tag{13}$$

$$U_2 = w_2 C, \tag{14}$$

$$U_3 = w_3(\alpha - \alpha_0)^2, \tag{15}$$

$$U_4 = w_4(\beta - \beta_0)^2, \tag{16}$$

and w_i are utility function weights, and α and β are the manipulation and elevation angles at the surgical target, respectively, with α_0 and β_0 representing their optimal values.

B. Constraints

To ensure that the obtained solutions are feasible, reachability of surgical targets should be guaranteed. This can be accomplished by including the joint limits into the constraints:

$$|\mathbf{q}| \leq \mathbf{q}_{max}, \tag{17}$$

where $\mathbf{q}$ represents the joint vector.

To address the collision avoidance between the patient's external anatomy and the active section of the manipulator, the maximum deflection of the instrument should be bounded. This requires that the maximum deflection angle between the $-\hat{\mathbf{z}}_3$ axis and the normal vector $\hat{\mathbf{n}}$ at the port of entry remains less than Ω, where Ω is the upper bound for the admissible range of deflections, i.e.:

$$|\arccos(-\hat{\mathbf{n}} \cdot \hat{\mathbf{z}}_3)| \leq \Omega. \tag{18}$$

The only equality constraint in the optimization is to ensure the unit magnitude of the resulting quaternions, given by:

$$\|\mathbf{Q}\| = 1. \tag{19}$$

Virtual fixtures imposed by the requirements of the operational environment, such as collision avoidance with the operating room table, comprise the remaining constraints.

VI. Case Study

In this section, the proposed planning strategy was implemented for a patient who was considered a candidate for CABG. Preoperative CT-images of the patient were be viewed and manipulated inside of an interactive 3D environment provided by the Atamai Viewer (Atamai, Inc., Calgary, Alberta). The intercostal spaces as well as the surgical targets, the LAD and the LIMA, were localized. This allowed a simple 3D model of the intrathoracic area to be constructed for further analysis, see Fig. 3.

A. Planning Results

Herein, the planning strategy developed in Section V was applied to the extracted geometric model in the case study. The results of this evaluation were assessed by an experienced surgeon and compared to clinically ideal port locations.

A variant of Sequential Quadratic Programming (SQP), based on the interior point method and the Broyden-Fletcher-Goldfarb-Shanno (BFGS) formula for Hessian update, was

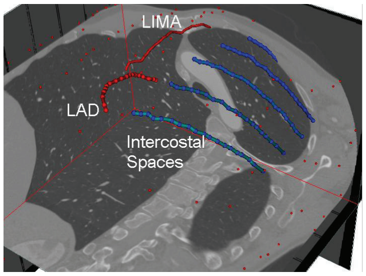

Fig. 3. The surgical workspace localized using a CT-scan in an interactive 3D environment provided by Atamai Viewer.

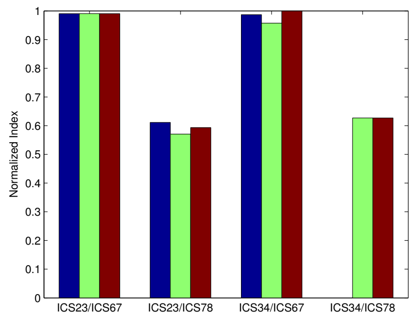

Fig. 4. Comparison between the normalized scoring indices obtained for port selection among the candidate ICS pairs.

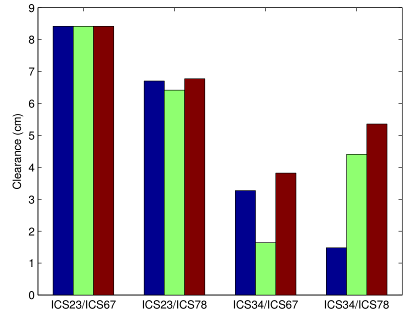

Fig. 5. Comparison between the achieved clearance measures for the candidate ICS pairs.

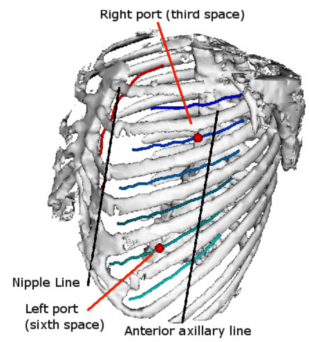

Fig. 6. Ports selected by the planning algorithm; the right port is closer to the anterior axillary line and the left port is closer to the nipple line.

utilized to solve the constrained nonlinear optimization problem. Due to the nonconvexity of the problem, a random initialization approach was used; however, the algorithm showed an acceptable degree of robustness to the random initialization. This was justified by the fact that a high percentage of trials led to similar or close solutions for a given pair of intercostal spaces.

The guidelines recommended in [19] were used for target point picking; the authors recommended that the ports should be selected such that both the distal and proximal ends of the LIMA as well as the mid-third of the LAD are reachable. In this case study, the LIMA was discretized into 10 points evenly distributed along the curve, including both endpoints, and 5 points were sampled on the midsection of the LAD.

Fig. 4 presents a comparison between the results obtained from the developed planning framework. An overall normalized index was attributed to each solution for four candidate pairs of intercostal spaces. Given each pair, three runs of the algorithm with random initial port positions were recorded. The clearance associated with each solution is depicted in Fig. 5. According to Fig. 4, by selecting the left port along the sixth ICS, the highest overall indices could be achieved. By selecting the right port in the second space, on the other hand, the risk of collisions will be dramatically reduced (see Fig. 5), although the worst clearance measure is still within the acceptable range of 2 cm, provided that the right arm is placed within the third space. The lowest clearance results from the ports selected in the spaces three and six, which is predictable, since these two spaces have the minimal distance among other candidates.

Interestingly, a strength of this algorithm was revealed when the surgeon chose the third and the seventh spaces for port placement for the same patient (as general guidelines suggest). However, the algorithm results show that both endpoints of the LIMA are only accessible from the posterior end of the seventh ICS. As a result, the port selected within this space is actually far below the Anterior Axillary Line (AAL) (see Fig. 6), in contrast to the common guidelines that recommend the left port to be moved up more medially on the chest somewhere between Nipple Line (NL) and AAL, depending on the chest geometry [20]. Also, the guidelines recommend that the right port be selected along the AAL (Fig. 6). In fact, the ports suggested by the algorithm in the seventh space do not comply with the guidelines simply because they do not lead to feasible port locations in that ICS. As shown in Fig. 4, the algorithm recommends that the left arm is placed in the sixth space. The fact that placing the right port in the second space may prove infeasible due to the potential collisions between the robot and the patient's shoulder, may encourage one to place the right port in the third space, which has been already justified by the surgeon as well. Yet these ports yield an acceptable clearance and manipulation angle. Fig. 6 shows the location of the ports suggested by the algorithm in the third and the sixth spaces.

Fig. 7 provides a preview of the active sections in action. The *da Vinci* arms have been configured based on the results of the planning algorithm in the third and the sixth spaces. Snapshots of the robot arms have been recorded as the instruments move between the target points. This visually proves that the solutions proposed by the planning framework

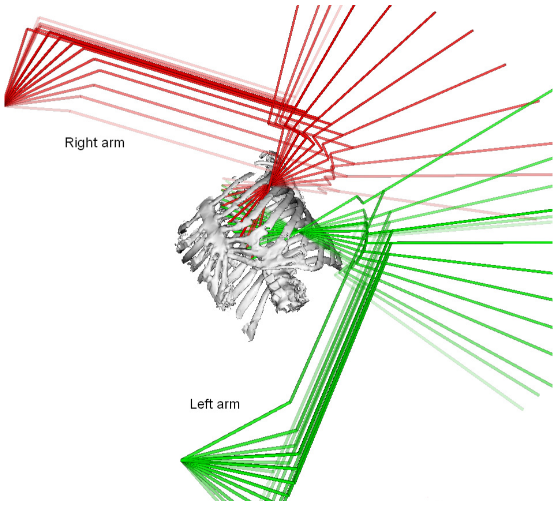

Fig. 7. A wire-frame preview of the *da Vinci* active sections in action, posed as recommended by the algorithm.

can reduce the risk of collisions during critical stages such as anastomosis and LIMA harvest, thanks to the concurrent port/pose planning.

VII. Conclusions and Future Work

A. Conclusions

In this paper, optimal placement of the *da Vinci* manipulator using preoperative CT images for robotics-assisted minimally invasive CABG was formulated as a constrained optimization problem. An objective function was proposed and the kinematic and geometric requirements of the problem were incorporated into the constraints. A modified measure of manipulability and a measure of clearance were proposed for inclusion into the objective function. The kinematic measure was shown to be well-defined and offered some refinements over other measures. Intraoperative collision detection during the critical stages of the procedure was implemented into the algorithm through a simplistic, yet nontrivial approach that provides fast minimum distance calculations without compromising accuracy. Finally, sequential quadratic programming was utilized to implement the constrained nonlinear optimization. Despite nonconvexity, the algorithm showed fair robustness to random initialization.

By incorporating the desired approach angles into the objective function, the surgeon's preferences were taken into account. The results of the case study showed compatibility of the framework with experienced surgeon's guidelines for port placement, and even improved those results by ensuring the feasibility of the solutions in the sense of clearance and target reachability.

B. Future Work

This paper outlines the initial results stemming from the ongoing development of a preoperative planning framework for RAMICS. As part of the future work, a number of extensions will be considered. The clearance measure will be made more comprehensive by accounting for the endoscopic arm, in addition to the instrument arms. When considering the endoscope, visibility is another index that can be improved through preoperative planning. Ultimately, extension of this work to other common cardiac procedures such as mitral valve repair is planned.

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