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Optimal Needle Grasp Selection for Automatic Execution of Suturing Tasks in Robotic Minimally Invasive Surgery

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Abstract

This paper presents algorithms for optimal selection of needle grasp, for autonomous robotic execution of the minimally invasive surgical suturing task. In order to minimize the tissue trauma during the suturing motion, the best practices of needle path planning that are used by surgeons are applied for autonomous robotic surgical suturing tasks. Once an optimal needle trajectory in a well-defined suturing scenario is chosen, another critical issue for suturing is the choice of needle grasp for the robotic system. Inappropriate needle grasp increases operating time requiring multiple re-grasps to complete the desired task. The proposed methods use manipulability, dexterity and torque metrics for needle grasp selection. A simulation demonstrates the proposed methods and recommends a variety of grasps. Then a realistic demonstration compares the performances of the manipulator using different grasps.

I. Introduction

In robotic minimally invasive surgery (RMIS), the surgical procedure is performed by a surgeon manipulating teleoperated robotic surgical tools instead of using manual instruments. Existing hardware, like Intuitive Surgical's da Vinci system (Intuitive Surgical, Inc), is able to help surgeon to perform intricate, precise surgical procedures. However, RMIS is usually tedious and time consuming, due to the nature of master-slave teleoperation. Intelligent robotic surgical assistants (IRSAs) that are capable of autonomously performing low-level surgical tasks have been proposed to improve patient health by enhancing surgeon performance, and reduce cost by decreasing operation time. In these years, numerous researches regarding autonomous and semi-autonomous robotic surgical systems are in progress [1].

In this project, we focus on automating one basic surgical task for IRSAs, namely, the automatic execution of suturing task in RMIS. A complete suturing task is composed of two subtasks: needle driving and knot tying. Jackson and Çavuşoğlu [2] proposed a needle path planning algorithm aimed at reducing tissue trauma by minimizing the interaction forces between the tissue and the needle specifically for autonomous suturing task. Chow et al. [3, 4] proposed improved methods for autonomously performing knot tying under vision guidance. These algorithms are specifically designed for autonomous execution of the tasks

taking into account specific challenges of automatic execution, such as, limited sensory feedback.

This paper focuses on solving the problem of optimally selecting needle grasps for IRSAs during needle driving. This is a key problem since improper needle grasps may result in multiple regrasps during performance of the desired task, leading to increased task completion times and even to task failures. For the surgical suturing task, uncertainties from random errors in sensory localizations and grasping of the needle are significant challenges, while they are not major concerns for teleoperated RMIS or open surgery, since the surgeon is in the loop. These concerns motivate us to provide IRSAs with a grasp which optimizes kinematic robustness to ensure that the task can still be successfully executed under slight variations in needle grasp configuration.

This paper proposes a systematic method to quantitatively compare different needle grasps for autonomously performing suturing tasks. The proposed techniques employ a feasibility algorithm, determining if performing a given reference needle trajectory is successful, and multiple metrics, quantifying the robustness of the robot's performance. The feasibility algorithm considers the robot's joint angle and joint torque limits as well as robot link-to-link, link-to-tissue and link-to-body-inner-surface collisions. The performance metrics assess the quality of needle grasp configurations by evaluating the manipulability, joint angle and joint torque distributions for execution of the reference needle driving trajectories. In this paper, the proposed methods are applied in a typical minimally invasive surgery (MIS) scenario for demonstration.

The rest of the paper is organized as follows. Related studies on automated suturing are discussed in Section II. The problem formulation and proposed methods are introduced in Section III. The specific details of the optimal needle grasp algorithm are presented in Section IV. A case study for validation of the proposed techniques and a realistic comparison experiment are presented in Section V. The conclusions are presented in Section VI.

II. Related Studies

Although to the best of the authors' knowledge, there are no earlier research studies that focus on optimal selection of needle grasp for suturing, there have been several earlier research studies in literature on automated suturing.

Kang et al. [5, 6] designed a special suturing instrument (especially for knot-tying) for autonomous suturing in RMIS. Currently there is a reusable suturing device named Endo 360⁰ for minimally invasive surgery (MIS) from EndoEvolution, LLC [7]. However, such special instruments are not widely used due to size limitations and complex designs.

Nageotte et al. [8, 9] proposed a path-planning method for stitching in MIS using a circular needle and a conventional 4 degrees-of-freedom (DoFs) needle holder.

Knoll et al. [10–12] proposed an approach of skill transfer from human to a multi-arm robot system through learning by demonstration. They automated the tasks of tissue piercing and

knot-tying in RMIS by learning. In this study, the needle was assumed to be normal to the jaws of the needle holder, and the needle was manually placed in the needle holder during the experiment.

Iyer et al. [13] demonstrated one single arm can automatically drive a needle through the tissue under the guidance of 3D camera. But they also did not consider the selection of the needle grasp.

A recent work by Ding et al. [14] has demonstrated the automation of surgical suturing by using dual-arm snake surgical robots. They used a minimal constraint suturing trajectory which allows the robot to have more dexterity by adjusting the orientations of the needle during insertion through tissue.

III. Problem Statement and Formulation

A. Problem Statement

In MIS, the robotic surgical instruments are introduced into the operating site inside the patient, which may be a natural or an artificially created cavity, through small incisions (Fig. 1). The goal of the optimal needle grasp selection is to determine the optimal position and orientation for grasping the surgical needle, given the entry port of the robotic instrument, the desired suturing location and direction that will enable successful needle driving. Here, we will specifically evaluate the robotic surgical system's ability to perform the suturing task, as it is arguably one of the most demanding dexterous manipulation tasks in MIS.

B. Desired Reference Trajectory for the Suturing Task

In surgical procedure, typically 1/2 or 3/8 circular shaped curved needles are used for suturing. For such a needle, the canonical needle trajectory with "good suturing technique" is a circular path that follows the natural curve of the needle [15, 16]. This paper uses this canonical needle trajectory as the desired reference needle trajectory that the surgical robotic system will perform. The needle-tissue interaction force required to perform the suturing is also specified along with the motion trajectory [15]. As the needle-tissue interaction force will inevitably vary in different cases because of inhomogeneity and inter-subject variability of tissue parameters [17–20], the specified force profile is interpreted as a sample profile.

C. Needle Grasp Parameterization

The configuration that the surgical manipulator grasps a needle determines how the desired reference needle trajectory is converted to the manipulator motions to perform the needle drive. The needle grasp with the surgical end-effector can be parameterized with 4 DoFs as shown in Fig. 2(a)¹. The gripper coordinate frame G is located on the tip of gripper. Its Z axis is perpendicular to the jaw of the gripper and its X axis points along the gripper. The needle coordinate frame N is placed on the tip of needle. Its Z axis is along the tangent at the tip of the needle and its X axis points to the center of the needle curve.

¹Please note that the specific configuration of the gripper is chosen for illustrative purposes here.

The kinematics of the pose of the needle grasp can be assumed that the needle moves starting from the tip of the gripper and then orientates three times along different axes. Specifically, ϑ_0 specifies the insertion translation along the negative X axis of G frame. ω_1 , ω_2 and ω_3 are three rotations that determine the orientation of the needle. ω_1 and ω_2 are defined to be around axes through the origin of the gripper frame, and ω_3 is defined to be around an axis through the center of the needle. In the zero configuration of needle grasp parameterization as shown in Fig. 2(b), when $\varphi_0 = \varphi_1 = \varphi_2 = \varphi_3 = 0$, the needle frame N is aligned with the gripper frame G . Here, φ_0 is the insertion translation distance for ϑ_0 . φ_1 , φ_2 and φ_3 are the corresponding rotation angles for ω_1 , ω_2 and ω_3 , respectively.

By implementing the fundamental knowledge of robotics from [21], the forward kinematics of the needle grasp is then given by

$$g_{GN}(\phi) = \begin{bmatrix} R(\phi) & P(\phi) \\ 0 & 1 \end{bmatrix}, \quad (1)$$

where

$$R(\phi) = \begin{bmatrix} s_1 s_3 - c_1 c_3 s_2 & -c_1 c_2 & -c_3 s_1 - c_1 s_2 s_3 \\ -c_1 s_3 - c_3 s_1 s_2 & -c_2 s_1 & c_1 c_3 - s_1 s_2 s_3 \\ -c_2 c_3 & s_2 & -c_2 s_3 \end{bmatrix}, \quad (2)$$

$$P(\phi) = \begin{bmatrix} r_n c_1 s_2 (c_3 - 1) - r_n s_1 s_3 - \phi_0 \\ r_n c_1 s_3 + r_n s_1 s_2 (c_3 - 1) \\ r_n c_2 (c_3 - 1) \end{bmatrix}. \quad (3)$$

Here, g_{GN} is a 4×4 matrix for expressing the orientation and position relations between Frame G and Frame N . c_1 and s_1 are abbreviations for $\cos \varphi_1$ and $\sin \varphi_1$, respectively, and similarly for the other terms. r_n represents the radius of the needle.

IV. Optimal Needle Grasp Selection

Needle grasp selection is essential for optimizing the performance of the manipulator during performing a suturing task. With given port locations, a tissue configuration, and a reference needle-driving trajectory, the optimization algorithm selects the needle grasp configuration by maximizing the kinematic robustness of the robotic manipulator. The needle grasp selection is only applied during needle driving motion, including choosing two needle grasps for needle insertion and needle extraction. As these two grasp choices are independent, they can be analyzed separately.

A. Feasibility Algorithms

For given a reference trajectory of the surgical robot's end-effector at a desired surgical site and a given port placement, the ability of the manipulator to successfully execute the

required motions is evaluated by the feasibility algorithm. In particular, the feasibility algorithm checks throughout the desired trajectory for:

1. *Robot reachability*,
2. *Robot joint limits*, including angles and torques,
3. *Robot link collisions*, including link-to-link, link-to-tissue, and link-to-body-inner-surface collisions.

The first criterion simply checks if the manipulator can reach a given target site by comparing the distance from target to entry port with the manipulator's shaft length.²

The second criterion determines whether the motion of the manipulator is within the robot's joint angle limits, and whether the specified needle-tissue force/torque are within the joint torque limits. The joint angle limits are checked with the required joint angles θ_i computed from the inverse kinematics of the surgical manipulators over the desired manipulator trajectories. The joint torque limits are evaluated by calculating the required joint torque τ_i from the specified needle force profiles using the manipulator Jacobian.

Given the geometries of the robotic manipulators, tissue configurations and operation environment, the third criterion checks if safe separation distances between any pair of non-attached links of the manipulator, between the manipulator links and tissue, and between the manipulator links and patient's inner body surface are maintained to guarantee collision-free trajectories.

B. Performance Metrics

A collection of three kinematic metrics are selected to quantify the quality of the needle grasp configuration.

The first metric that is considered is the distribution of the manipulability measure of the manipulator along the reference trajectory. Manipulability is defined as the ratio of the smallest singular value to the largest singular value of the manipulator Jacobian³ [21],

$$\mu(\theta) = \frac{\sigma_{\min}(J(\theta))}{\sigma_{\max}(J(\theta))}, \quad (4)$$

which quantifies the ability of the manipulator to move freely in all directions in the workspace. The manipulability metric (W_μ) can then be defined as the time average of the cumulative manipulability along the trajectory,

²It is important to note that the reachability condition is actually a subset of the condition on the validity of the robot joint limits. However, here, we check the robot reachability separately, as it is usually much simpler to evaluate than the robot joint limits, which requires the full solution of the inverse kinematics of the robotic manipulator. This way, it is possible to avoid computation of the full inverse kinematics, if the reachability condition is violated, reducing the overall computational load.

³In this study, we use the body Jacobian, as it is independent of the choice of the base frame of the manipulator [21].

$$W_\mu = \frac{1}{T} \int_0^T \mu(\theta(t)) dt, \quad (5)$$

where, T is the duration of the desired trajectory and $\theta(t)$ is the desired motion trajectory defined over a time interval $[0, T]$. The manipulability measure, $\mu(\theta)$, is equal to 0 at singularities of the manipulator and equal to 1 at isotropic configurations. Therefore, maximizing the manipulability metric, W_μ , along the trajectory of the manipulator is desirable to improve the kinematic quality of the needle grasp.

The dexterity of a robotic manipulator is significantly decreased when the manipulator is close to its joint angle limits. So it is desirable to stay away from the joint angle limits as much as possible for maintaining dexterity. Accordingly, a performance metric is proposed to quantify the distribution of joint angles of the actuated joints in their range of motions. Specifically, the weighting function for each joint angle θ_i is defined as follows:

$$f_i(\theta_i) = \frac{4|\theta_i - \theta_{i,mid}|^2}{|\theta_{i,max} - \theta_{i,min}|^2}, \quad (6)$$

where

$$\theta_{i,mid} = \frac{\theta_{i,max} + \theta_{i,min}}{2}, \quad (7)$$

and $\theta_{i,max}$ and $\theta_{i,min}$ are respectively the maximum and minimum values of the joint angle i . The total cost for joint i along the given desired trajectory $\theta_i(t)$, $t \in [0, T]$, is then defined as

$$D_i = \frac{1}{T} \int_0^T f_i(\theta_i(t)) dt. \quad (8)$$

The dexterity metric (W_θ) can then be defined as the sum of all joints' total costs:

$$W_\theta = \sum_{i=1}^N D_i = \frac{1}{T} \sum_{i=1}^N \int_0^T f_i(\theta_i(t)) dt, \quad (9)$$

where N is the total number of the degrees of freedom of the system. $W_\theta \in [0, 1]$ and minimizing the dexterity metric W_θ improves the dexterity of the manipulator along the given desired trajectory.

As mentioned in the feasibility algorithm, the joint torques can be calculated through the Jacobian of the manipulator, given the needle-tissue interaction forces along the needle trajectory. The third metric, W_τ , focuses on the joint torque levels, quantifying the distribution of each joint torque with respect to its joint torque limit during the performance of the suturing task. Similar to the joint angle case described above, the weighting function for each joint torque τ_i is defined as:

$$h_i(\tau_i) = \frac{4|\tau_i - \tau_{i,mid}|^2}{|\tau_{i,max} - \tau_{i,min}|^2}, \quad (10)$$

where

$$\tau_{i,mid} = \frac{\tau_{i,max} + \tau_{i,min}}{2}, \quad (11)$$

and $\tau_{i,max}$ and $\tau_{i,min}$ are the maximum and minimum possible torque values for the joint i . The total cost for joint i along the given desired needle-driving trajectory $\tau_i(t)$, $t \in [0, T]$, is then

$$Q_i = \frac{1}{T} \int_0^T h_i(\tau_i(t)) dt. \quad (12)$$

The torque usage metric (W_τ) is then defined as the sum of all joints' total costs as:

$$W_\tau = \sum_{i=1}^N Q_i = \frac{1}{T} \sum_{i=1}^N \int_0^T h_i(\tau_i(t)) dt. \quad (13)$$

$W_\tau \in [0, 1]$ and minimizing the torque usage metric W_τ reduces the joint torques that need to be applied by the manipulator along the given desired trajectory. In other words, this metric increases the capability of the manipulator to handle uncertain force deviations from the nominal force due to deviations of the actual needle trajectory away from the nominal trajectory.

Algorithm 1

Needle Grasp Selection Algorithm

```

input :
  Suturing site; Suturing trajectory; Port location;
  Manipulator's forward and inverse kinematics
output:
  O: a matrix of  $O_k$ 
   $O_k$ : performance metric values for needle grasp k
begin
  for each potential needle grasp do
    for each step in desired trajectory do
      angle  $\theta \leftarrow$  use inverse kinematics
      torque  $\tau \leftarrow$  use body Jacobian
      manipulability  $\mu(\theta) \leftarrow$  use Eq. 4

       $Fea \leftarrow$  check feasibility algorithm
      if  $Fea$  fails then
         $\perp$  Break
      if  $Fea$  not fail then
         $W_\mu \leftarrow$  calculate by Eq. 5
         $W_\theta \leftarrow$  calculate by Eq. 9
         $W_\tau \leftarrow$  calculate by Eq. 13
         $O_k \leftarrow$  calculate by Eq. 14
      else
         $O_k \leftarrow$  Infinity
    return optimal grasp  $\leftarrow$  find maximum  $O_k$ 

```

It is important to note that it is possible to combine these three individual kinematic metrics into a single cumulative performance metric in various ways to quantify the kinematic robustness of the manipulator performing a suturing task with a given needle grasp. In this study, a simple linear combination of the three kinematic metrics is used. Namely, the combined performance metric is defined as

$$O = \sigma_\mu W_\mu - \sigma_\theta W_\theta - \sigma_\tau W_\tau, \quad (14)$$

where σ_μ , σ_θ and σ_τ are the scale ratios of the individual kinematic metrics W_μ , W_θ and W_τ . By maximizing the manipulability metric W_μ and minimizing the dexterity metric W_θ and the torque usage metric W_τ subject to the feasibility conditions, the system will ensure that the robot has sufficient dexterity and avoids the singular configurations during performance of the suturing tasks.

C. Needle Grasp Selection Algorithm

The algorithm of selecting optimal needle grasp is presented in Algorithm 1. Given the entry port location and the desired task specification, a collection of pre-specified needle grasp

candidates are investigated by the selection algorithm. θ is the joint angle vector calculated using the inverse kinematics from the end effector's motions. τ is the joint torque vector calculated through the manipulator Jacobian from the end-effector wrench. The manipulability index $\mu(\theta)$ is calculated from (4). Fea represents the result of the feasibility test which indicates whether the corresponding motion can be completed, as discussed in Section IV-A.

The optimization for needle grasp selection typically needs to be performed using a brute-force search as the metrics considered are not convex and may have local extrema points. The computational performance of the algorithms in a specific case will be discussed in more details in Section VI.

If desired, the computations required for optimal grasp selection can be precomputed and stored as a look-up table. Specifically, this look-up table has 6 parameters as inputs which define the transformation relationship between the entry port coordinate frame F and the desired suturing location coordinate frame V , denoted by g_{FV} . The look-up table outputs 4 parameters which define the needle grasp configuration, g_{GN} , on basis of the dexterity or manipulability index.

V. Results

A. Description of the suturing task

The case study is a robotic laparoscopic surgery (minimally invasive abdominal surgery) scenario. The task and robot configuration are specified as shown in Fig. 1. Specifically, the robot kinematics is assumed to be a 2 DoFs wrist (+ gripper specified by the gripper coordinate frame G) at the end of a tool shaft that goes through a 4 DoFs (3 rotations + 1 insertion translation) entry port, which is specified by the coordinate frame F .⁴ The suturing site is specified by the suturing location coordinate frame V and the desired suturing line is defined to be along the Y axis of V frame (shown with the red line in Fig. 1). A Taper Point SH 1/2 Circle 27 mm needle from Ethicon is used in this simulation. For simplicity, all possible locations for entry ports are assumed to lie over a hemisphere.⁵ The global coordinate frame B is placed on the center of the hemisphere.

In this case study, a simplified internal anatomy is considered. The suturing site is assumed to occur on the tangent plane of the tissue, and the collision detection algorithm only checks if the robot links collide with this tangent plane instead of the real tissue surface of internal organs. This approximation simplifies geometry and allows an intuitive interpretation of the results. The simplification is not by any means a requirement of the proposed approach.

⁴Please note that the specific kinematic configuration of the wrist, and the constraint on the possible entry port locations are not fundamental to the presented method, and are chosen for illustration purposes only.

⁵In laparoscopic surgery, carbon dioxide gas is pumped into the peritoneal cavity for creating a pneumoperitoneum for a better view inside the abdomen and creating an operating volume [22, 23]. Figuratively, the shape of the pneumoperitoneum looks like a hemisphere. Although it is a gross approximation, the abdominal surface can be simply approximated as a hemisphere in this case study as a demonstration. A realistic anatomical representation will be used in the second case study.

B. Simulation Result for Optimal Needle Grasp Selection

In Section IV-B, the performance metrics, namely, manipulability (W_μ), dexterity (W_θ), and joint torque usage (W_τ) are proposed for optimizing needle grasp. In this case study, the ultimate value of the combined performance metrics is computed through (14), where weights $\sigma_\mu = 1$, $\sigma_\theta = 1$, $\sigma_\tau = 1$ are used.

In the needle grasp selection, the entry port location, the target location, and the reference needle trajectory need to be pre-specified. A total of 3410 possible needle grasp configurations are evaluated.

For the needle insertion, 244 needle grasps out of the total 3410 possible grasps are feasible. The optimal selection among the 244 feasible choices is shown in Fig. 3(a), with the optimal metric value, 0.4215. Similarly for the needle extraction, 1042 needle grasps out of the total 3410 possible grasps are feasible. The optimal selection with the optimal metric value of 0.4690 is shown in Fig. 3(b).

Fig. 3 shows the results of the optimal needle grasp in a black solid curve and the distribution of all feasible needle grasps in cyan dotted curves, (a) for needle insertion and (b) for extraction. The magenta solid curves show 63 and 197 grasp configurations with metric values at least 90% of the optimal metric values in the cases of needle insertion and needle extraction, respectively. From the results, one can see that the grasp robustness metric varies smoothly with small changes in grasp configurations, as the optimal needle grasp choice is located among a multitude of secondary choices.

C. Comparisons of various needle grasps

Three different needle grasps for needle insertion actions are chosen. The selected configurations are $[6\ 0\ 0\ 175^\circ]$, $[6\ 0\ -15^\circ\ 175^\circ]$ and $[6\ 10^\circ\ 10^\circ\ 175^\circ]$. These four parameters in the brackets refer to $[\phi_0\ \phi_1\ \phi_2\ \phi_3]$ in (1) to represent a needle grasp configuration. $[6\ 0\ 0\ 175^\circ]$ is the optimal needle grasping pose. $[6\ 0\ -15^\circ\ 175^\circ]$ and $[6\ 10^\circ\ 10^\circ\ 175^\circ]$ are the competitors 1 and 2 for the needle grasping poses. Both competitors are feasible needle grasps.

The robotic testbed system used in the experiments includes a vision system and a 6 DoFs ABB IRB 140 robot [24] equipped with a 3 DoFs robotic laparoscopic instrument designed in house [25], as shown in Fig. 4. In the experiment, the robotic laparoscopic instrument obeying the kinematic constraint from a port, stitched a needle into a tissue phantom (Complex Tissue Model, Simulab, Seattle, WA) and drove it through.

The wrist motions of the laparoscopic instrument for these three needle grasps are shown in Fig. 5. (10) implies that the wrist motions of needle grasp, $[6\ 0\ 0\ 175^\circ]$, (yaw and pitch motions), are much better than the needle grasps of $[6\ 0\ -15^\circ\ 175^\circ]$ and $[6\ 10^\circ\ 10^\circ\ 175^\circ]$. The joint motions of wrist with the optimal needle grasp are closer to their zero positions.

The trajectories of the ABB tool for needle insertion actions are shown in Fig. 6. The black, magenta, and cyan curves represent the ABB robot with the optimal needle grasp, competitor 1, and 2. The Fig. 6 shows that the ABB robot with competitor 1 needle grasp

moves the longest distance in magenta during the needle insertion action. The length of the cyan curve is the shortest. The length of black curve is close to the shortest length.

In summary, the needle grasping pose of $[600175^\circ]$ which is the configuration selected by the proposed algorithm is more preferred based on joint motion ranges. The same comparisons can also be conducted for needle extraction actions.

VI. Conclusions

This paper proposes a method to choose optimal needle grasping poses for surgical suturing tasks in RMIS. The selected optimal needle grasping pose optimizes the manipulability and dexterity of the surgical system. This algorithm also suggests a range of suboptimal needle grasps which are approximately optimal, with metric values more than 90% of the value of the optimal needle grasp. It guarantees the reliability of needle grasps in the procedure by increasing the system's tolerance of random errors in the system, such as in vision sensory system and motion sensors. This work demonstrates the usability of this selection algorithm in autonomous surgery in the future.

The computation time of the proposed algorithm for optimal needle grasp selections is an important concern for clinical applicability of the methods. The computation takes less than 4 minutes to analyze 3410 candidate grasping poses on a desktop equipped with Intel® core i7-960 CPU @ 3.20 GHz and 12.0 GB memory, running 64-bit Microsoft Windows® 7 operating system. The algorithm is implemented in Matlab® R2012b with a parallel computing under 4 workers. We expect that a more optimized implementation, such as in C/C++, and if necessary, execution on a higher performance computing cluster, would provide sufficient speedup for online execution satisfying the fast-paced requirements of a clinical application.

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Fig. 1.

Coordinate frames used in the analysis, including the global coordinate frame, two entry port coordinate frames, two tip coordinate frames and a suturing location coordinate frame.

Robot A is equipped with a needle driver, and Robot B is equipped with a pair of forceps.

The incision/suturing location coordinate frame (V) is set up as the Z axis perpendicular to the horizontal plane of the hemisphere and XY axes lying in this plane. The entry port coordinate frames (F_{c_i}) are set up as the Y axis pointing to the center of the hemisphere and XZ axes tangent to the surface of the sphere. The directions of X and Z axes will depend on the pose of the surgical manipulator on the entry port.

Fig. 2.

Needle grasp parameterization. (a) Illustrations of a needle grasp pose and definitions of gripper coordinate frame (G) and needle coordinate frame (N). The origin of the Frame G is at the tip of the gripper. The Z axis is perpendicular to the jaw of the gripper. The X axis points along the gripper out. The origin of the Frame N is located on the tip of the needle. Its Z axis is along the tangent at the tip of the needle and its X axis points to the center of the needle curve. (b) Zero configuration of the needle grasp parameterization, when $\varphi_0 = \varphi_1 = \varphi_2 = \varphi_3 = 0$.

Fig. 3.

The results of optimal needle grasp selection. One curve represents one potential needle position. The optimal needle grasp for the given needle driving task is shown in black. The needle grasps with at least 90% of the optimal metric value are shown in magenta. Other feasible needle grasp configurations are shown in cyan. The bold black line represents the needle holder. The curves represent the shapes of the needles. (a) Grasps for needle insertion, (b) Grasps for needle extraction.

Fig. 4. Experiment setup for suturing tasks. The system includes a vision system and a 6 DoFs ABB IRB 140 robot [24] equipped with a 3 DoFs robotic laparoscopic instrument [25].

Fig. 5.

Yaw and pitch motions of wrist for three samples of different needle grasping poses. The configuration of optimal needle grasp is $[6 \ 0 \ 0 \ 175^\circ]$. The configuration of the first needle grasp competitor (competitor 1) is $[6 \ 0 \ -15^\circ \ 175^\circ]$. The configuration of the second needle grasp competitor (competitor 2) is $[6 \ 10^\circ \ 10^\circ \ 175^\circ]$. The four parameters refer to $[\varphi_0 \ \varphi_1 \ \varphi_2 \ \varphi_3]$ in (1).

Fig. 6. Needle insertion trajectories of the ABB robot. The black, magenta, cyan curves represent the trajectories of the ABB robot with optimal needle grasp, needle grasp competitor 1, and competitor 2.