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# Optimal Base placement of the Da Vinci System based on the Manipulability Index

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**Abstract.** During the preoperative planning of robotically assisted laparoscopic surgery, one of the most critical issues for the success of the surgery is the trocar port placement (the special tools which are entering the patient's body) and the placement of the entire robotic system (position and orientation). Suitable placement affects the robot's dexterity, reachability in the surgical field, manipulability and visibility in the workspace which are necessary for the successful outcome of a laparoscopic surgical procedure. Even today, distinguished and experienced surgeons have difficulty solving such problems because of the high redundancy of the robots. The main aim of this study is to propose an approach for suboptimal base placement of the Da Vinci Surgical System, in order to maximize the performance of the robot in the surgical site. An aggregated dexterity measure in surgical points is formulated based on the robot configuration dependent manipulability index. The ADM is used as the objective function for the determination of the best robot base location in order to obtaine high dexterity performance in the surgical operation area. A genetic algorithm is used to search for the optimal base location.

**Keywords.** Da Vinci Surgical System, Base Placement, Manipulability Index, Genetic Algorithm

## 1. Introduction

Robotic assisted minimally invasive surgery (MIS) combines the advantages of laparoscopic surgery with the advantages of open surgery with regard to the complexity of operations and the need for wide surgical field of view. The complexity of operations is achieved by the ability of robots to mimic the human wrist movements and perform 360°motions and the wide surgical field of view is obtained through the stereoscopic vision by magnifying the image even by 15 times. The robot does not perform surgeries autonomously, but it is used as an auxiliary device which reduce the time to complete the invasion and enhances the capabilities of laparoscopic surgery.

This paper investigates the best placement of the base of the robotic system *Da Vinci Surgical System* (Da Vinci for simplicity) related to the position and the orientation of the robotic base during a surgery. The Da Vinci provides surgeons with such detail and precision in their handling, that allows them to operate the robotic surgery as if it was an open surgical procedure through very small holes. A better placement of the robotic system can increase the exploitation of the robot mobility and joint velocities of the surgical tools. The easiness of the motion in all directions is improoved considerably.

Furthermore, this paper proposes a method for the best placement of the Da Vinci robot based on a dexterity index. The best placement of the robot is evaluated using an aggregated dexterity measure based on the manipulability index commonly used in robotics. In order to find the configuration that performs best, a genetic algorithm is used with that fitness function. The importance of the proposed approach is based on the fact that the existing advantages of robotic-assisted surgery can be furthermore enhanced, if the joint velocities and accuracy of the robot can be highly exploited. This can be achieved by placing the robot base relative to the surgery site so that the end effector operates in the area of the workspace where the configurations required to operate are of high dexterity and accuracy.

## 2. Related works

There are several works in the last few years, which are related to determining the optimal trocar position and pose selection of the Da Vinci Robot in minimally invasive surgery (MIS). Tabaie et al. (1999) developed a guideline for the port placement of the robot during a endoscopic coronary artery bypass graft surgery (ECABG). This work required a large amount of information and had incorrectly assumed that the internal anatomy of the patient is indicated accurately from the outer chest wall. After these guidelines Lehmann et al. (2001) tried to validate already selected port placements. Therefore a simulation platform was developed to determine the location of the ports.

Cannon et al. (2003) introduced an optimization algorithm for the best port placement which used a vector that gives the ideal angle between the surgical target and the instrument. Moreover Adhami and Coste-Manière (2002) applied also an optimization algorithm for optimal port placement among all possible locations. The possible locations are given from the surgeon and thus these positions vary according to the surgeon's experience. In this work, approximations are used of the Da Vinci system instruments using primitives as cylinders and spheres. Trejos and Patel (2005) focused on determining the best port placement and pose selection of the robot for an endoscopic cardiac surgery based on the dexterity optimization. This algorithm used a global isotropy index and a global performance index based on the distribution of the inverse of the condition number over the entire manipulator workspace. Sun and Yeung (2007) proposed an algorithm, which identifies the optimal placement of the trocar with evaluation criteria: the dexterity, the reachability and the visibility in inaccessible areas into the patient's body.

Moreover Khampitak et al. (2010) wanted to design a small and ergonomic camera manipulating robot with less interferences with the surgeon. Therefore they composed an experiment in live porcine model to study the suitable motion range in port positions. Liu et al. (2011) using the "MicroHand A" robotic system also proposed an optimal port placement planning method based on the overall workspace of Robotic Assisted Cholecystectomy (RAC), which is acquired by analysis of each subspace of the procedure. The range of the motion of instrument or endoscope can be acquired by analysis of motion, and accordingly, a new measure called the interference index, is introduced on the basis of these ranges of motion.

To our knowledge, there are not many studies on the determination of the placement of the robot's base except Wu et al. (2010), which discussed the pose planning problem, referred to as the initial configuration of stationary (passive) joints. That paper describes a pose planning method for the minimally invasive robotic surgery system that was under development and tested the feasibility of this method.

## 3. Problem Definition

### 3.1. The Da Vinci System

The Da Vinci Surgical System is a tele-manipulation system that consists of an surgeon's console, a patient cart with four interactive robotic arms, a high-performance vision System and surgical instruments. In this paper, the Da Vinci Robot is modeled only to have a movable base with one arm. The arm is consisted by the robot mechanism, which has 6 passive joints $\begin{bmatrix} t_1 & \theta_2 & \theta_3 & \theta_4 & \theta_5 & \theta_6 \end{bmatrix}$ and the active robot arm with the instrument holder which is consisted by 6 active joints. The model of the active robot arm is divided into a positioner $\begin{bmatrix} \theta_7 & \theta_8 & t_9 \end{bmatrix}$, which moves the end-effector in order to reach the target. The second part is the instrument, which is configured as a wrist, holding the end-effector and determining its' direction in the patient body ($\begin{bmatrix} \theta_{10} & \theta_{11} & \theta_{12} \end{bmatrix}$). The total mobility of the system is equal to fifteen (15) with six (6) degrees of freedom (DoF). A combination of the simplified section of the active section presented in Trejos and Patel (2005) and the kinematic model presented in Sun et al. (2007) is used to represent the D-H parameters of the system, shown in table 1.

In this paper the best placement of the movable base and the best configuration of the robot mechanism based on the manipulability index is considered.

### 3.2. Manipulability Index

The dexterity measure that was chosen for this application is the manipulability index. The concept of dexterity was introduced by Salisbury and Craig

| Link | Parameter | $\theta_i$ | $\alpha_i$ | $d_i$ | $a_i$ |
|---|---|---|---|---|---|
| | | Robot Mechanism | | | |
| 1 | $t_1$ | 0 | 0 | $t_1$ | $l_1 = 172.5$ |
| 2 | $\theta_2$ | $\theta_2$ | 0 | $h_2 = 85.5$ | 0 |
| 3 | $\theta_3$ | $\theta_3$ | 0 | $h_3 = 163$ | $l_3 = 413$ |
| 4 | $\theta_4$ | $\theta_4$ | 0 | $h_4 = -57.75$ | $l_4 = 362$ |
| 5 | $\theta_5$ | $\theta_5$ | $-\pi/2$ | $h_5 = -85$ | $l_5 = 110$ |
| 6 | $\theta_6$ | $\theta_6$ | $\pi/2$ | 0 | $l_6 = 350$ |
| | | Active Joints | | | |
| 7 | $\theta_7$ | $\theta_7$ | $-\pi/2$ | $h_7 = 170$ | 0 |
| 8 | $\theta_8$ | $\theta_8$ | $-\pi/2$ | 0 | 0 |
| 9 | $t_9$ | 0 | $\pi/2$ | $t_9$ | 0 |
| 0 | $\theta_{10}$ | $\theta_{10}$ | 0 | 0 | 0 |
| 11 | $\theta_{11}$ | $\theta_{11}$ | $-\pi/2$ | 0 | 0 |
| 12 | $\theta_{12}$ | $\theta_{12}$ | $\pi/2$ | 0 | 0 |

Tab. 1. D-H parameters of the Robotic Arm ($h_i$ is the horizontal distance in mm, $l_i$ is the link length in mm)

(1982) but the mathematical definition was introduced by Yoshikawa (1985) and generally expressed by eq. 1

$$w = det(J) \quad (1)$$

The manipulability index is calculated by eq. 2

$$w = \sqrt{det(J \cdot J^T)} \quad (2)$$

where $J$ is the Jacobian of the manipulator as defined by the instantaneous kinematics.

If $w$ is relatively high then the surgeon will have the ability to move the Da Vinci tools fast in the cartesian space, since the joint velocities have high contribution to the surgeon tool velocity. In configurations where $w$, is low the surgeon must put more effort in terms of time to move the tool.

Since, the robot has 6 DoF, $J$ will be evaluated using the kinematic parameters and variables of the active robot arm. In the following, the model of the operating room where the Da Vinci system is working will be modeled.

### 3.3. Modeling of the operating room

A simplified layout of the operating table with the Da Vinci Robot, the surgeon and the patient is shown in fig. 1. A local coordinate system is attached to selected bodies in the robotic surgical intervention. Along with the definition of the local coordinate systems, an overview of the surgical ward is required. Placing the patient on the operating table, the position of the surgical bed and the location of the robotic system give a full picture of the spatial configuration in which the study is based. The main frames under consideration are five namely: The Operating Table $\{T\}$ which is defined as the global coordinate system, the Region of Interest $\{Roi\}$ where the surgeon is operating through the Da Vinci Robot, the Robot Base $\{BD\}$ which defines the position and orientation in a plane parallel to the global $\{XY\}$ of the base of the Da Vinci Robot, the Robot Mechanism $\{RM\}$ and the active joints ($\{7-12\}$) of the Da Vinci arm where the operating instrument are attached.

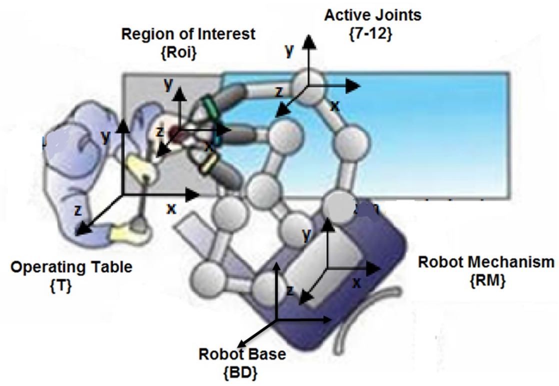


Fig. 1. Operating room with the coordinate system

The kinematic problem under consideration is defined as:

$${}^{T}_{ROI}T = {}^{T}_{BD}T \cdot {}^{BD}_{RM}T \cdot {}^{RM}_{ROI}T \quad (3)$$

where ${}^{T}_{ROI}T$ is the transformation of the Table coordinate system $\{T\}$ to the region of interest $\{ROI\}$, ${}^{T}_{BD}T$ is the transformation of the Table coordinate system $\{T\}$ to the Robot Base $\{BD\}$, ${}^{BD}_{RM}T$ is the transformation of the Robot Base $\{BD\}$ to Robot Mechanism $\{RM\}$ and finally ${}^{RM}_{ROI}T$ is the transformation from the Robot Mechanism to Region of Interest $\{ROI\}$.

The robot base to table transformation is given by eq. 4

$${}^{T}_{BD}T = \begin{bmatrix} \cos\theta_b & -\sin\theta_b & 0 & P_x \\ \sin\theta_b & \cos\theta_b & 0 & P_y \\ 0 & 0 & 1 & -800 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

where, 800 mm is the distance of the floor to the operating table. It is assumed that the surface of the table is, and remains during the operation, parallel to the floor.

As it is reffered, the Da Vinci Robot is modeled only to have a movable base with one arm, and ${}^{BD}_{RM}T = I_4$. Therefore the kinematic equations are trasnformed to:

$${}^{RM}_{ROI}T = ({}^{T}_{RM}T)^{-1} \cdot {}^{T}_{ROI}T \quad (5)$$

Solving eq. 5, all the configurations of the active robot arm $\theta_{7-12}$ are determined, and the manipulability index can be calculated through the Jacobian matrix.

### 3.4. Optimisation Problem

In this paper, the optimisation problem is defined as the best placement of the Da Vinci robot base determined by $\theta_b, P_x, P_y$ and the configuration of the Robot Mechanism $\theta_{RM}$ that provides the best dexterity. This is obtained by maximizing the minimum value of the manipulability index for a given number of points $P_i$ in the Region of Interest. Therefore, the optimisation problem is formulated as follows:

$$X^* = arg(\max_X(\min_i(\max_{\theta_{7-12}}(w_i(X,\theta_{7-12}))))) \quad (6)$$

where, $X = \{\theta_b, P_x, P_y, t_1, \theta_2, \theta_3, \theta_4, \theta_5, \theta_6\}$ and $i$ is indexing the point with the minimum $w$. Without loss of generality three points, $P_1, P_2, P_3$ critical to the surgery, are selected in the region of interest. For a given position and orientation of the Da Vinci base and a given configuration of the Robotic Mechanism, the inverse kinematic problem is solved and all the configurations of the active robot joints are calculated. For every solution of the inverse kinematic problem the Jacobian matrix and then the manipulability index are calculated. For every point $P_i$, the best $w$ is determined. The minimum value of $w$ for the three points is selected to map the given $X$. Since the dimensionality of the problem is high, a genetic algorithm is utilized using the manipulability index as the fitness function.

### 3.5. Genetic Algorithm

In an environment such as the configuration space of the Da Vinci a steerable search strategy is needed, such as the Genetic Algorithm (GA), that provides a good chance of success. The use of GA in robotics applications is not a new concept, in the literature they have been applied in the optimization of robot trajectories, motion control, behavior based-logic, task scheduling or even robot design optimization. For this reason, a basic genetic algorithm is applied to obtain the best configurations for the variables that characterize the base of the robot. The fitness function $f$ of the GA is the following:

$$f = \begin{cases} 0, \textit{ if any } P_i \textit{ out of the workspace} \\ \min_i(\max_{\theta_{7-12}}(w_i(X,\theta_{7-12})))), \textit{ else} \end{cases} \quad (7)$$

Therefore, the chromosomes used are encoded by nine real numbers.

$$gen = \{\theta_b, P_x, P_y, t_1, \theta_2, \theta_3, \theta_4, \theta_5, \theta_6\} \quad (8)$$

Where, $\theta_b \in [-\pi, \pi]$, $P_x \in [500, 1200]$, $P_y \in [1200, 1500]$, $t_1 \in [-800, 500]$, $\theta_{2-6} \in [-\pi/2, \pi/2]$. Without any loss of generality, the 3 points recommended by the surgeon according to the surgery on the operating table ($P_1 = [1000, 500, 400], P_2 = [1200, 550, 350], P_3 = [900, 600, 300]$) near the area of the task are selected. The techniques used in the genetic algorithm are the elitist selection strategy, single point crossover and uniform mutation. The elitist strategy is a selection method according to which the current best solution is always copied in the "tank" of the mates, skipping to the next generation without modification of genetic characteristics, which means without going through the phase of reproduction. This method is important because it ensures that good possible solutions of a generation are not corrupted due to admixtures with others. In the single point crossover method, a single point is randomly selected for each pair, where the genetic information is swapped. Single point crossover is selecter compared to other multipoint operators since the size of the chromosome is small. Concerning the uniform mutation a random number in the bounds of every gene is selected, and it is selected compared ot other operators since the genes are encoded by real numbers.

## 4. Results

By trial and error, the control parameters of the Genetic Algorithm were found and are shown in table 2. All the computations are implemented using Matlab 2012a, on a single thread of an Core 2 Duo T7300 Laptop with 2GB of RAM, and a full execution took about 30 minutes. The configuration of the Da Vinci

| Parameters of the Genetic Algorithm | |
|---|---|
| Population Size | 450 |
| Maximum Generations | 400 |
| Crossover Probability | 0.9 |
| Mutation Probability | 0.005 |
| Fitness Value of Best Gene | 197299.732007 |

Tab. 2. Values of the GA parameters and the best value of the fitness function that is resulted

robot that was found to be the most dexterous in the configuration shown in table 3

| Robot Configuration | |
|---|---|
| $\theta_b$ | -1.568156 |
| $P_x$ | 603.263522 |
| $P_y$ | 1245.975336 |
| $t_1$ | 484.498904 |
| $\theta_2$ | 1.713891 |
| $\theta_3$ | -1.272411 |
| $\theta_4$ | 3.137125 |
| $\theta_5$ | -1.429115 |
| $\theta_6$ | -1.263280 |

Tab. 3. The sub-optimal placement and configuration of the Da Vinci robot in terms of manipulability

It is worth noting that even with different control parameters of the Genetic Algorithm, the best configuration and placement of the robot varied slightly, indicating the stability of the proposed method. The resulting configuration is illustrated using Matlab and the Robotics Toolbox Corke (2011), in order to check the feasibility of the desired posture. As a result, the position of the robot in relation to the operation table in the surgical workspace at the reference configuration is shown in fig. 2. The average runtime of the algorithm is about 15 mins The base

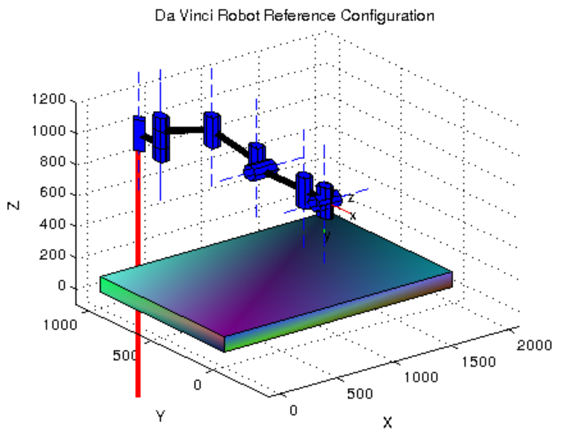


Fig. 2. The Da Vinci robot at the reference configuration

placement as well as the configuration of the robot mechanism is shown in fig. 3. Both of those fig-

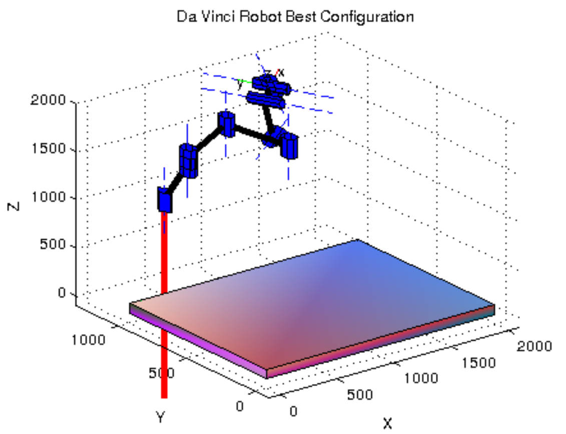


Fig. 3. The Da Vinci robot at the best resulted configuration

ures illustrate the robot in the workspace with the last 6 joints at their reference configuration ($\theta_{ROI} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$). Through the inverse kinematics, the 3 points on the operating table are reachable and the robot configuration has the highest achievable manipulability index and the 1st point of them is shown in fig. 4. To show the difference in performance achieved by our best derived configuration (shown in green), the translational ellipsoid is plotted in the 3 points opposed to a bad configuration given by $[-\pi/2, 603, 1246, 480, \pi/3, -1.27, \pi, -1.42, -1.26]$ (shown in red). Since the entire ellipsoid is 6 dimensional and thus cannot be plotted, we isolated the rows corresponding to the translational velocities and performed a singular value decomposition on that $3 \times 6$ jacobian matrix obtaining the 3 dimensional translational ellipsoid. In fig. 5 and fig. 7 the green ellipsoid outweights the red one in almost every direction giving a better velocity transmission from the joints to the end effector in all directions. In fig. 6 however, the red ellipsoid has better performance over the direction of the z-axis. Since the manipulability index provides an analogy to the volume of the ellipsoid, that is an effect that cannot be overcomed, given that the volume of the green (best) ellipsoid is larger than that of the red (bad) ellipsoid. If the desired output is a better performance over every direction, then a different dexterity measure can be used, such as the minimum singular value $\sigma_{min}$.

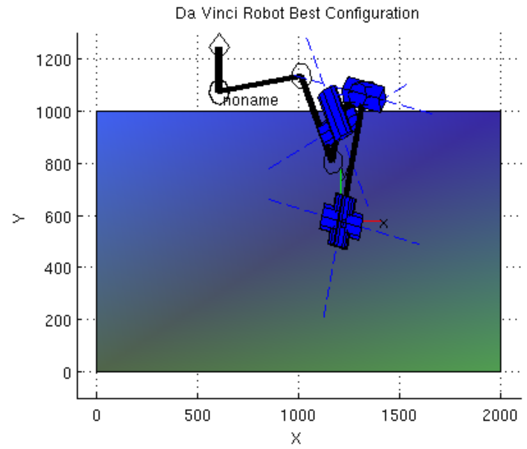


Fig. 4. The Da Vinci robot at the best resulted configuration operating at $P_1$

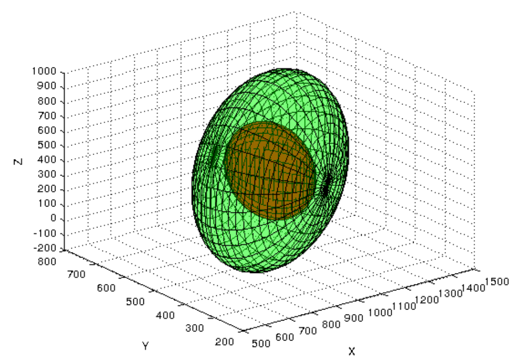


Fig. 5. The ellipsoid of the Da Vinci robot operating at $P_1$. Green color: At the best resulted configuration, Red color: At a bad configuration

## 5. Discussion

### 5.1. Work Estimation

The results of this paper provide important information about which robot base placement and configuration o fthe robor mechanisms can improve the movements of the active joints. The aim of this

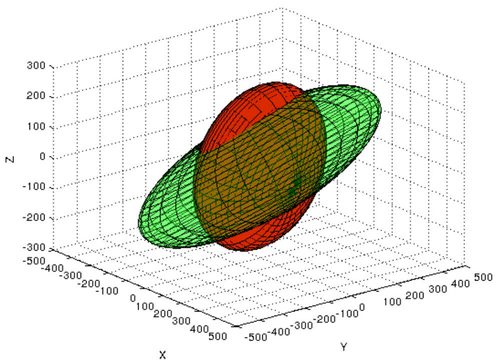


Fig. 6. The ellipsoid of the Da Vinci robot operating at $P_2$. Green color: At the best resulted configuration, Red color: At a bad configuration

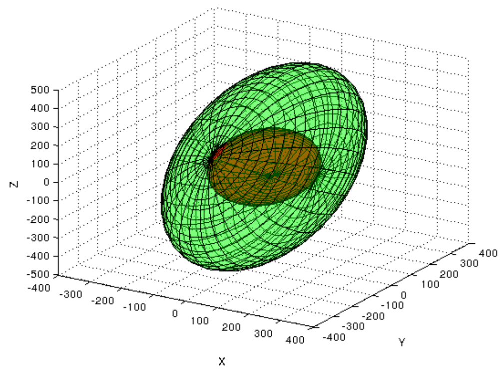


Fig. 7. The ellipsoid of the Da Vinci robot operating at $P_3$. Green color: At the best resulted configuration, Red color: At a bad configuration

research is to provide another motive for using robots in the field of medical science and to consolidate the robotic-assisted minimally invasive surgery, which offers so many advantages for patients and doctors. Furthermore, the proposed process in this work can inform and contribute to the experience of many doctors, who are working in the field of robotic surgery, giving them advice and providing new practices for a more successful surgery with less trauma and faster recovery.

### 5.2. Future Work

In spite the fact that this paper presents a better placement of the robotic base of the Da Vinci System, future work can include advanced strategies using other dexterity indices as an objective function. The dexterity measures are able to describe the mapping of force, velocity and control resolution from the joint space to cartesian space of the robotic arm and they can be used for local configuration optimality. For example the 'Condition Number'. is a dexterity measure which can be used additionally in this methodology considering the accuracy and isotropy. By considering dexterity measures such as the minimum singular value, a lowest threshold of velocity transmission can be set that must be met in the workspace area. According to that criteria, the derived optimal anatomy will produce configurations that can operate in the se(3) meeting that specification.

Moreover this paper uses the assumption that the robot operates in a 'Point to Point' method, in which the arms move to exact poses in the workspace without caring about the trajectory. Future work will focus on the development of an optimization method that takes into account the entire volume of the surgical operation and provides the best placement and configuration of the robot in its workspace. In this case, the recently introduced concept of the Area Dexterity MeasureValsamos et al. (2013) will be used to provide the best operating area of the robot's joints.

Lastly, this study develops a guideline to be used for all of the 4 robotic arms that are available in the Da Vinci System although in this paper only one of the arm is used. The cooperation of all 4 robotic arms considering possible collisions and dexterity measures for the entire Da Vinci system is a study that could be performed.

## 6. Conclusions

This work examines the limitations and the capabilities in the use of the Da Vinci surgical system to perform operations in small cavities and the role of the base which helps to manipulate the instruments properly. As a result the surgeon can reach the surgical site (internal of the abdomen of the patient) and the target (gall bladder) with maximum dexterity. Research has not been focused to give results for the pose selection of the robot in the operating room using the whole robot mechanism including the base.

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