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Shahram Payandeh
Simon Fraser University

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Design of spherical parallel mechanisms for application to laparoscopic surgery

Temei Li and Shahram Payandeh

Experimental Robotics Laboratory, School of Engineering Science, Simon Fraser University, Burnaby, British Columbia (Canada) V5A 1S6

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SUMMARY
This paper addresses an optimal study of workspace for spherical parallel mechanism for laparoscopic surgery. The spherical parallel manipulator has been selected because of its characteristics. Two designs have been studied for maximizing their workspaces; a haptic device, as part of training system, and a laparoscope holding mechanism. The laparoscope holding mechanism has to satisfy additional constraints by minimizing the occupied space above the patient. The objective is to solve design problem to offer the maximal workspace for such mechanisms. The design of a haptic interface and the laparoscope holding mechanism based on the optimal parameters are presented. This paper presents a Genetic Algorithm (GA) approach for selecting optimal design parameters for maximizing workspace of spherical parallel mechanism.

KEYWORDS: Laparoscopic surgery; Spherical parallel mechanisms; Workspace study; Genetic algorithms.

1. INTRODUCTION

Since the 1980s, laparoscopic surgery has been widely used to substitute traditional open surgery. The main advantages are short recovery time, decreased risk of infection, less pain/trauma for the patient and reduced hospital stay/cost. On the other hand, surgeons have limitations in direct vision of the operation area, lack of dexterous manipulation, force feedback and control of surgical instruments.

Major challenges in designing laparoscopic mechanism are maximizing workspace inside patient's abdominal cavity and reducing space as well as weight of the mechanism outside the body. For example, occupied space outside of laparoscope holding mechanism should be small to offer more space for surgeons and surgical instruments. The space above abdomen is occupied by several surgical tools; therefore, the laparoscope holding mechanism should be as compact as possible. To solve these problems in laparoscopic surgery, assisting mechanisms were proposed by Faraz, Neisius, and Melzer.[1–5]

A laparoscope holding mechanism has to achieve three spherical degrees of freedom (DOF) with respect to the incision point at abdominal wall (three rotations about X, Y, Z-axes of a frame at the incision point). The pivot center of the mechanism is located at the incision point. For a laparoscope holder in laparoscopic surgery, commercial products are available on the market, such as Computer Motion's endoscope positioning robot, which is a serial robot with revolute joints.[6] The Charoenkrung Pracharak Hospital in Thailand[7] also developed a serial manipulator, adjustable desk lamp-like, laparoscopic camera holder.

In our design, spherical parallel mechanism, with rotating joints, has been chosen because of simple type actuating mechanism as well as kinematic characterization and the workspace.[8] The characteristics of parallel manipulator offer excellent stiffness, high precision and light weight. However, limited workspace and more complex kinematics representation have been the main disadvantages. There are many studies regarding estimation of the workspace volumes of serial manipulators. However, there are only few papers addressing numerical method for studying the workspace volume of parallel manipulators. In this paper, in order to increase the workspace volume of such manipulators, the design parameters of spherical parallel manipulator are optimized to find the maximum workspace. A Genetic Algorithm (GA) is used in the simulation processes to identify the optimal design parameters of the manipulators. Gosselin et al. have developed kinematics equations of spherical three degrees of freedom parallel manipulators.[9,10] The kinematic formulations were applied to solve workspace for the parallel manipulators. Tsai and Soni also applied numerical method to solve workspace problems.[11] An optimal design had been also presented by Vijaykumar.[12]

This paper is organized as follows: First, the notation and kinematics model of spherical parallel manipulator are introduced. Then, GA approaches for the optimal design parameters to achieve maximal workspace volume are developed. Third, design parametric studies were discussed to verify the results of GA. The design model from optimal parameters for laparoscope holding mechanism and a haptic device are then presented. Finally, concluding remarks and some suggestions for future works are given.

2. NOTATION AND KINEMATICS

2.1 Notation and design parameters

Figure 1 shows a schematic of a spherical parallel mechanism. The reference frame $O(X, Y, Z)$ defines the fixed coordinate system and the reference frame defining the rotating platform is $C(X, Y, Z)$. The rotating platform is

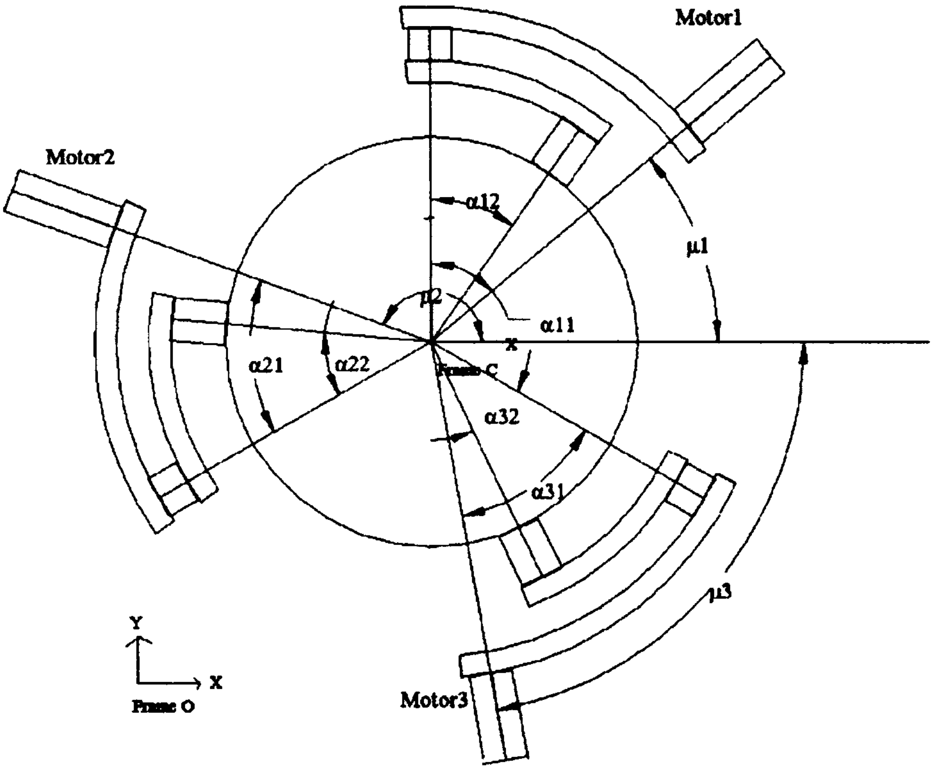

Fig. 1. Definition of design parameters.

connected to the ground through three branches, each of which comprises two intermediate arms and three revolute joints.

The design parameters under consideration are:

(i) Actuator Angles (μ_1, μ_2, μ_3, β_1, β_2, β_3): μ_1, μ_2, μ_3 represent the angles measured between the X-axis of the reference frame $O(X, Y, Z)$ and the center of actuators 1, 2 or 3, respectively. These three actuators are fixed to a spherical surface with respect to the reference frame $O(X, Y, Z)$. β_1, β_2, β_3 in Figure 2 represent the angles between X-Y plane of the reference frame $O(X, Y, Z)$ and axes of actuators 1, 2 and 3, respectively. These angles are subject to the following geometrical constraints. $0 \leq \mu_1 < \mu_2 < \mu_3 < 2\pi$ and $0 \leq \beta_1$, β_2, $\beta_3, < \pi$.In the design of laparoscope holder, additional constraints for β_i are introduced ($\pi/6 \leq \beta_1$, β_2, $\beta_3, < \pi/2$)

(ii) Branch arm angles (α_{11}, α_{21}, α_{31}, α_{12}, α_{22}, α_{32}): all three branches have two linkages. The angle of these arms are defined by α_{11}, α_{21}, α_{31} which stand for the angles between the three actuator axes and their corresponding revolute joints of outer arms. Similarly, α_{12}, α_{22}, α_{32} are the angles between the two revolute joints of the branches. These angles are also subject to the following geometrical constraints: (a). $\alpha_{11} + \alpha_{21} + \alpha_{31} < 2\pi$; (b). $\alpha_{12} + \alpha_{22} + \alpha_{32} < 2\pi$.

2.2 *Kinematic modeling*

In this section, a kinematic model proposed by Gosselin et al.[13] is applied for solving the kinematic parameters. The kinematic diagram is shown in Figure 3. u_i, i = 1, 2, 3 are directed along the axes of the revolute joints of the actuators. The unit vector v_i, i = 1, 2, 3 are the axes of the revolute joints of the platform. The unit vectors corresponding to the revolute joints connecting the outer arm and inner arm on each branch are designed by w_i, i = 1, 2, 3. The vector v_i defined in Frame O (the fixed Frame) can be obtained by rotation matrix Q in terms of vector v_{ic} in Frame C (The Frame attached to the platform):

$$v_i = Q[v_{ic}],\ i = 1, 2, 3 \tag{1}$$

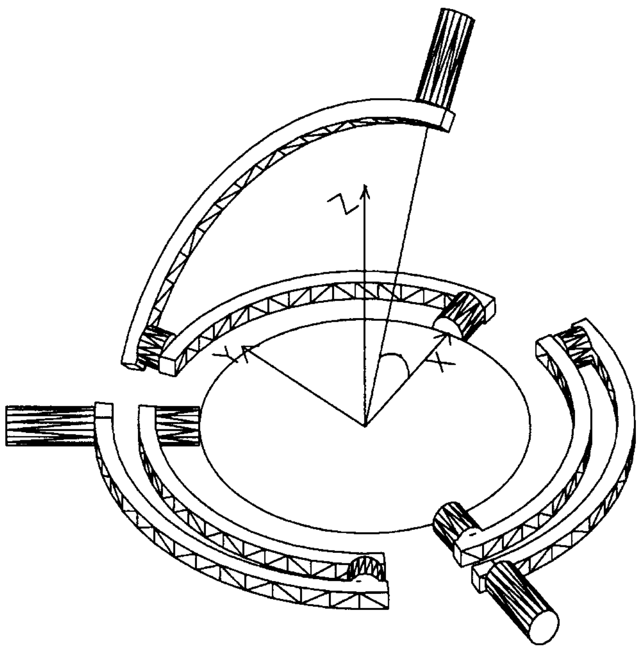

Fig. 2. General schematic drawing of a manipulator $\beta_1 \neq 0$, β_2, $\beta_3 = 0$.

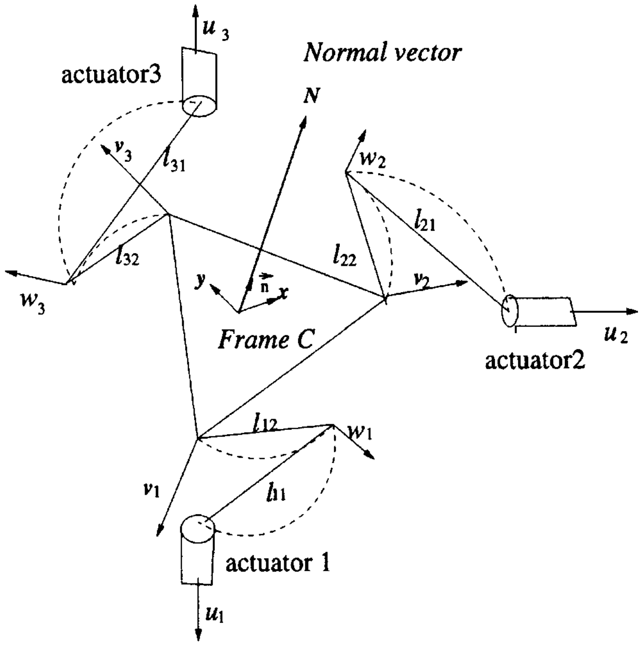

Fig. 3. The kinematic model.

where the rotation matrix and unit vectors, v_{ic} are defined as:[10]

$$v_{1c}=\begin{bmatrix}0\\0\\1\end{bmatrix}$$

$$v_{2c}=\begin{bmatrix}\sin\gamma_2\\0\\\cos\gamma_2\end{bmatrix}$$

$$v_{3c}=\begin{bmatrix}\cos\psi_2\sin\frac{\gamma_2}{2}\\\sin\psi_2\\\cos\psi_2\cos\frac{\gamma_2}{2}\end{bmatrix}$$

Where the γ_2 and ψ_2 is defined as:

$$\gamma_2=arcsin\left(\frac{\sqrt{3}}{2}\sin\beta_2\right)$$

$$\psi_2=\beta_2+arctan\left(\frac{\sin\frac{\gamma_2}{2}}{\sqrt{3-4\sin^2\frac{\gamma_2}{2}}}\right)$$

be calculated for a given actuator rotating angle θ_i. A general form of equation that can describe the workspace volume is given as:

$$WorkspaceVolume=1/3*\pi*\sin(\gamma^2)*\cos(\gamma) \qquad (3)$$

Where γ is the boundary loci of normal vector corresponding to the symmetric centerline of workspace.

3. APPLICATION OF GENETIC ALGORITHM

The genetic algorithm, GA, is a stochastic global search method that mimics the metaphor of natural biological evolution.[14] GA was selected as an optimizing tool because it has benefits of both weak and strong search methods.[15] Strong methods, such as numerical optimization procedures, perform a search in an informed manner by function gradients. Weak methods such as random or exhaustive procedures search in a uniformed method by extensively sampling the design space. Weak methods are expensive but more likely to find global optima; strong methods are inexpensive but more likely to settle by local sub optima. GA operate with a strong progression toward improved designs, together with the weak operations of probabilistic selecting, crossover and mutation. GA methods had been successfully applied to optimization problems like scheduling, optimal control, transportation problems and engineering design. They are robust because they simultaneously evaluate many points in the search space and more likely converge toward the global optimal solution. Recently, GA had been used to solve engineering design problems by Altus, Chapman et al.[16,17] Cam-shape design optimization was one of the design problems solved by GA.[18] We applied GA to the analysis of the workspace similar to the parametric variation used in heuristic optimization.[19,20]

In a GA search, the goal is to find the maximal workspace volume. Initially, the algorithm randomly generates 100 sets of different design parameters (chromosome string) as the first generation parents. Design parameters, such as actuator angles and arm angles, are set up as 5 degree increments so that μ_i, β_i, α_{ij} can be 0, 5, 10, . . . Next, the workspace volume with respect to each set of design parameters is calculated. Third, the parents are ranked by their workspace volume. Each parent has a fitness number, which measures how fit it is for the environment. The fitness number is assigned to the parents proportional to the rank of parents. The parent with the larger workspace volume has a higher fitness value on the ranking list. The parent with the largest workspace volume is ranked as the first or best parent. Parents are selected by fitness values to produce offspring. As shown in Figure 4, by applying the middle point crossover method, the first six chromosomes of parent one are combined with the last six chromosomes of parent two to produce offspring one. The first six chromosomes of parent two and the last six chromosomes of parent one produce offspring two.

3.1 Genetic algorithm formulation

GA operates on a population of potential solutions by applying the principle of survival of the fittest to produce better solutions. For each generation, the process of selecting parents produces a new set of approximations. GA analyzes simultaneously a number of potential solutions called population, consisting of an encoded parameter set. Typically, a population is composed of a range of solutions between 30 and 100.

The GA formulation for workspace analysis has the following steps:

(i) **Selection**: Selection is proportional to the fitness from the population of parents. It is necessary to take a balance between the "good parents" and "bad parents"

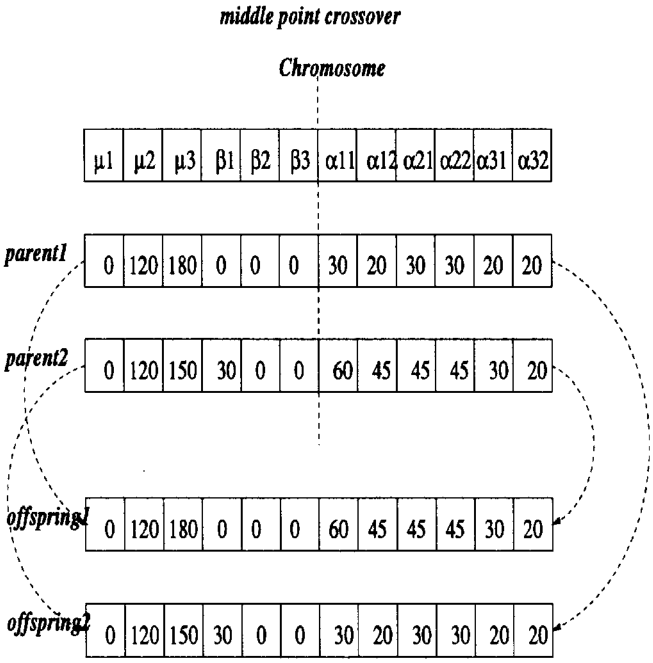

Fig. 4. An example of a crossover model.

because various chromosomes from all parents are needed.

Chromosomes are composed of six actuator position angles μ_1, μ_2, μ_3, β_1, β_2, β_3 and six arm angles α_{11}, α_{21}, α_{31}, α_{12}, α_{22}, α_{32}. Actuator positions are also presented as angles to be consistent in unit. The workspace volume of each member in the population is calculated to represent a fitness number.The population, therefore, is ranked in a fitness number for crossover.

There is a possibility for each parent to be selected for all of the population.

(ii) **Crossover**: The crossover action combines different chromosome strings to generate new offspring strings. One point crossover is mostly used for GA. Goldberg[14] defined the partially mapped crossover (PMO) by using two crossover points. The selection between these points defines an interchange mapping.

The crossover method in this paper is set to be two different types: (a) Random position where a crossover point was generated randomly. This number is greater than one and less than the total number of chromosomes, and (b) Middle crossover where the crossover point is at the middle of a tota1 chromosome string.

(iii) **Mutation**: Mutation will be applied when the offspring is the same as one of its parents. In general, the mutation is worked with a single chromosome. A chromosome will be created by randomly reassigning a value to one of its genes, which, in this paper, are those position angles.

In this paper, the mutation rate, or the probability to conduct a mutation depends on the identity of parents and offspring. The chromosome of every offspring will be compared with parents. The mutation will be performed only if the offspring has an identical chromosome as parent. If the parent and offspring are identical, the mutation changes any chromosome randomly. The mutation offers a versatile solution to prevent offspring converging toward local maximum.

(iv) **Replacement**: The replacement produces a new generation offspring from the current parents into the new parents. The best solution of a new offspring is compared with the best solution of their parents. The completely new generation will be replaced by the offspring while the offspring is better than that of parents. If the best offspring is not as good as the best parent, the crossover process will be repeated to generate new offspring. The GA flowchart is represented in Figure 5.

3.2 GA results

Computational results that are important for discussion regarding parameter adjustments are given as follows:

Selection: The selection decides the number of times or trials which parents to be crossover. The fitness number should strike a balance between the converge speed and avoid being trapped by a local optimal. The calculation can be speeded up by adjusting fitness value.

Crossover: The results show that there was little difference between randomly selected or middle point crossovers. This can be explained by the fact that different selecting strategies come out with similar results because of large varieties of chromosomes.

Replacement: Several types of replacement have been applied, such as incremental replacement and total replacements. The incremental replacement replaces only 20 percent of worst parents. The incremental replacement did not offer good results because the chromosomes of the offspring were very similar. After several generations, the offspring will be identical, converging to a local optima. If we place a mutation stage for this replacement, the converging rate will be faster toward global optima. The comparison of best offspring and best parent will always offer a better solution.

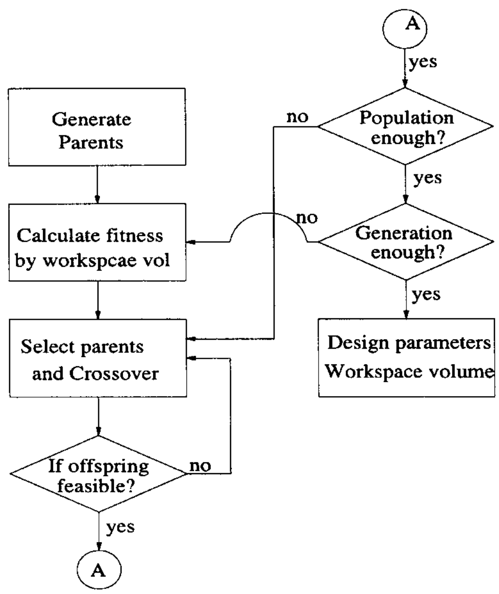

Fig. 5. Flow chart for a GA application.

Fig. 6. The generation vs. workspace volume.

Population: The population numbers of 30, 70 and 100 are all applied in this study. The population with larger number offers faster converging rates. It was found that applying GA for a heuristic search of optimal parameters, the number of generation plays an important role.

Figure 6 shows that the number of generations also affects the final solution. More generations will produce better solutions. However, after a certain number of generations, the solution should converge to optima. According to the GA computation, the population number of 100 gave best results.

The optimal parameters selected by GA are presented in Table 1. The final workspace volume for a laparoscope holder is smaller than the workspace volume of a haptic device because extra constraints, such as the degrees of β_i, have been applied.

4. OPTIMAL DESIGN SPECIFICATION

The optimal design specification for both a laparoscope holder and a haptic device are summarized in Table 1. Two CAD models were developed in accordance with these specifications. Figure 7 is the optimal design for a laparoscope holder. An additional actuator could be installed on the platform to move the laparoscope up and down. This actuator should be placed on the upper sphere of the platform to avoid interference. The optimal design for the haptic device is illustrated in Figure 8. This mechanism can be used as part of a surgical training system or teleoperation system. These designs were developed in a unit vector configuration which can provide greater flexibility for adjusting to different sizes by a multiplication factor. This technique was also applied when a collision check was performed. The vector is extended to a line model when checking the interference. It was ensured that

Table 1. The optimal parameters for both a laparoscope holder and a haptic device from GA.

Design parameter	Laparascope holder	Haptic device
μ_1	0	0
μ_2	120	120
μ_3	240	240
$\beta_1\beta_2\beta_3$	30, 30, 30	0, 0, 0
α_{1i}	50, 50, 50	50, 50, 50
α_{2i}	50, 50, 50	50, 50, 50
Workspace volume	1.07	1.22

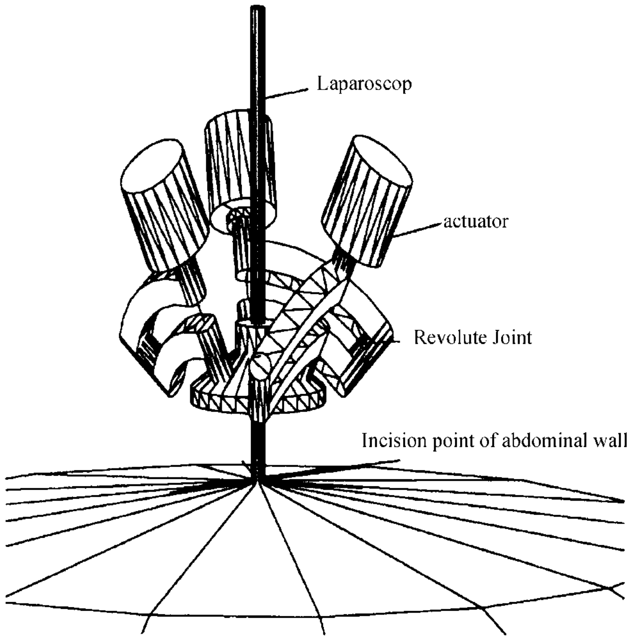

Fig. 7. Optimal spherical parallel mechanism design for a Laparoscope Holder.

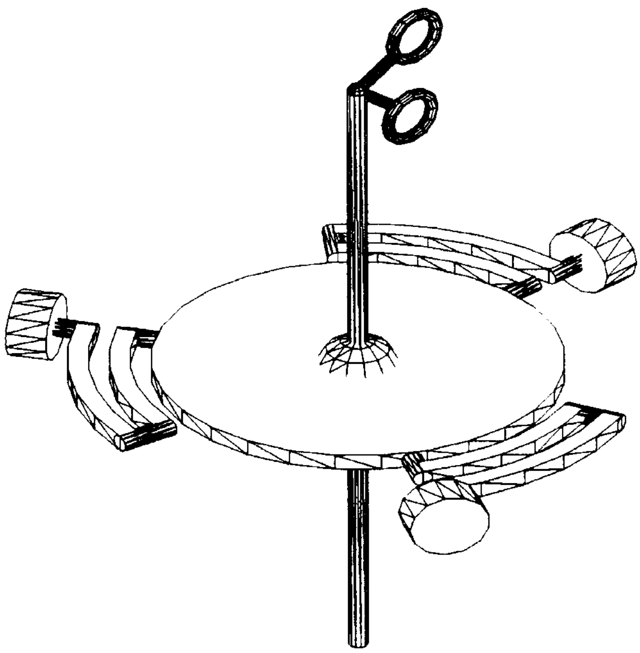

Fig. 8. Optimal parallel spherical mechanism design for a Haptic device.

the mechanisms were interference free in their workspaces. Figure 8 shows a schematic of the laparoscope holder mechanism based on the optimal design parameters given in Table 1.

5. CONCLUSION AND FUTURE WORK

In this paper, the workspace study of a spherical parallel mechanism applied to laparoscopic surgery has been investigated. The Generic Algorithm method is used to search for optimal design parameters. The workspace analysis of a three DOF spherical parallel manipulator is studied and optimal solutions have been addressed. The collision checking for laparoscope holding mechanism has been performed among the linkages and the normal direction of moving platform; it represents interference checking for the motion of mechanism with itself.

The interference with the abdominal wall has not been investigated. To check the interference, the abdominal wall can be modeled as semi-spherical or parabola surface. This surface model can be of use if the movement of the laparoscope holding mechanism touches the abdominal wall.

The nominal models studied are represented by unit vectors. Having determined the optimal design parameters, it is necessary to consider the machining process and set-up consideration. Our final goal is to build a compact, lightweight, large workspace three DOF laparoscope holder mechanism and a haptic training device for laparoscopic surgery.

References

1. B. Neisius, P. Dautzenberg and R. Trapp, "Robotics manipulator for Endoscopic handling of Surgical Effectors and Cameras", *Proceedings of 1st International Conference on Medical Robotics and Computer Assisted Surgery* (1994), pp. 1–7.
2. A. Melzer, "Intelligent Surgical Instrument Systems", *J. Endoscopic Surgery and Allied Technologies* **1**, 165–170 (1993).
3. A. Faraz, "Mechanisms and Robotic Extender for Laparoscopic Surgery", *Ph. D. Thesis* (Simon Fraser University, 1998).
4. A. Faraz and S. Payandeh, "A Robotic Case Study: Optimal Design of Laparoscopic Positioning Stand", *Int. J. Robotics Research* **17**, 986–995 (1998).
5. A. Faraz and S. Payandeh, *Engineering Approaches to Mechanical and Robotic Design for Minimally Invasive Surgeries* (Kluwer Academic Publishers, 2000).
6. Computer Motion Inc., http://www.computermotion.com/
7. S. Kornsuthisopon, "New Release of the Boonpong Laparoscopic Camera Holder", *Aust. N.Z. J. Surg.* **69**, 141–143 (1999).
8. Y. Koseki, T. Arai, K. Sugimoto, T. Takatuji and M. Goto, "Design and Accuracy Evaluation of High Speed and High Precision Parallel Mechanism", *Proceedings of IEEE International Conference on Robotics and Automation* (1998), pp. 1340–1346.
9. C. Gosselin and J. Sefrioui, "On the Direct Kinematics of Spherical Three-Degree of Freedom Parallel Manipulators with a Coplanar Platform", *ASME Journal of Mechanical Design* **116**, 587–593 (1994).
10. C. Gosselin, L. Perreault and C. Vaillancourt, "Simulation and Computer-Aided Design of Spherical Parallel Manipulators", *Proceedings of IEEE International Conference on Robotics and Automation* (1994), pp. 145–151.
11. Y. Tsai and A. Morgan, "Solving the Kinematic of the Most General Six and Five Degrees-Of-Freedom Manipulators by Continuation Methods", *ASME Journal of Mechanical Design* **107**, 189–200 (1985).
12. R. Vijaykumar, K. Valdron and M. Tsai, "Geometric Optimization of Serial Chain Manipulator Structures for Working Volume and Dexterity", *Int. J. Robotics Research* **5** No, 2, 91–103 (1986).
13. C. Gosselin, J. Sefrioui and M. Richard, "On the Direct Kinematics of Spherical Three-Degree-of-Freedom Parallel Manipulators with a Coplanar Platform", *ASME Journal of Mechanical Design* **116**, 587–593 (1994).
14. J. Holland, *Adoption in Natural and Artificial Systems* (The University of Michigan Press, Ann Arbor, MI, 1975).
15. D. Goldberg, *Genetic Algorithms in Search, Optimization, and Machine Learning* (Addison-Wesley, Reading, MA, 1989).
16. S. Altus, I. Kroo and P. Gage, "A Genetic Algorithm for Scheduling and Decomposition of Multidisciplinary Design Problems", *ASME Journal of Mechanical Design* **118**, No. 4, 486–489 (1996)
17. C. Chapman, K. Saitou and M. Jakiela, "Genetic Algorithms as an Approach to Configuration and Topology Design", *ASME Journal of Mechanical Design* **116**, No. 4, 1005–1012 (1994).
18. A. Alander and J. Lampinen, "Cam Shape optimization by genetic algorithm", *Genetic Algorithms and Evolution Straightedges in Engineering and Computer Science* (John-Wiley & Sons, 1998).
19. Z. Michalewicz, *Genetic Algorithms + Data Structures = Evolution Programs* (Springer, 1996).
20. N. Ansari and E. Hou, *Computational Intelligence for Optimization* (Kluwer Academic Publishing, 1997).