Robust Design Synthesis of Spherical Parallel Manipulator for Dexterous Medical Task

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Abstract This paper deals with the design synthsesis of a spherical parallel manipulator (SPM) for a dexterous surgery task. A considerable effect of manufacturing errors on the workspace and particularly on the dexterity of the mechanism is noted. Thus, the use of nominal values of the design vector generated by deterministic optimization may be erroneous. The effect of these errors on the mechanism workspace and dexterity is then studied and a Robust approach combining genetic algorithms (GA) and Monte Carlo Simulation (MCS) is presented to lead to an SPM with a low-sensitive dexterity to manufacturing errors. The results are finally discussed through an example.

Keywords Spherical parallel mechanism · Robust design synthesis · Dexterous task · Manufacturing errors · Dexterity · Monte Carlo simulation

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1 Introduction

Several studies dealt with the 3-RRR spherical parallel manipulators (SPM) [2, 4, 5]. The platform of the mechanism is moving over a spherical surface around a fixed center of motion. In the bibliography, several studies covered a wide range of characteristics such as workspace [3], kinematic analysis [5] and design parameters (DP) optimization [2]. This characteristic is suitable for our application of minimally invasive surgery since the surgeon is operating with tools through small incisions in the body patient. Indeed, this work is part of a project to design and fabricate a teleoperation system for minimally invasive surgery. An experimental study of this technique based on motion capture was held in previous work [4] to characterize the task workspace. Figure 1 (left) illustrates the expert surgeon operating with tools on a training station (Pelvis Trainer). Figure 1 (right) represents the workspace of the used tools (a clamp and a needle holder) identified by motion capture. Each tool operates in a conical space with a maximum half vertex angle of 26°. However, despite being an over constrained mechanism; few studies were interested in the effect of manufacturing errors on the SPM. A1-Widyan et al. [1] evaluated through a stochastic method the translational displacement of each cylindrical joint in the 3-RCC architecture. In a previous work [4], we were interested in finding the optimal dimensions of a SPM with a given workspace. The effect of the manufacturing errors (ME) on the platform position and dexterity, was also studied. In this paper, the effect of these errors on the dexterity of the mechanism is reviewed and a robust design strategy is proposed. The dexterity of the manipulator resulting from the deterministic optimization showed a high sensitivity to ME, which led us to adopt a new strategy combining genetic algorithms (GA) and a Monte Carlo Simulation (MCS) [7] to synthesize a spherical manipulator with a low-sensitive dexterity to ME. The results of this approach are then presented and the performances of the obtained manipulator are discussed.

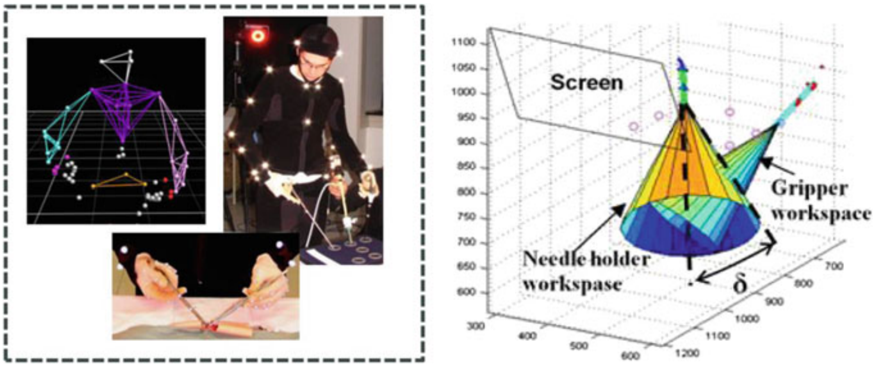

Fig. 1 Experimental study of surgical task. *Left*: reconstruction of the surgeon operating. *Right*: experimental workspace

2 Kinematics of the SPM

Figure 2 (left) presents the 3-RRR architecture of the proposed SPM. Three identical legs A, B and C relate the base to the platform. Each leg of the SPM is made out of two links and three revolute joints. The three actuated revolute joints with the base have orthogonal axes $\mathbf{Z}_{1k}$ *(k = A, B and C)*. All the axes of the joints are intersecting in a single point, the center of motion of the platform.

Figure 2 (right) shows the geometric parameters of one leg. The angles α, β, γ are, respectively, between the first two joint axes, the second and the third one, and between the third axis and the platform axis.

The three legs of the SPM are identical and the actuated joint axes are located along the base frame axes **X**, **Y**and **Z**, respectively. The workspace of the platform is given by the intersection of the three workspaces of three legs, which are considered each as a spherical serial kinematic chain.

The motion of the SPM is generated by only revolute joints. The kinematics of the mechanism can be described by the following relation:

$$\mathbf{Z}_{2k} \cdot \mathbf{Z}_{3k} = cos(\beta) \tag{1}$$

where $\mathbf{Z}_{2k}$ and $\mathbf{Z}_{3k}$ are respectively the axes of the second and the third joint of each leg and detailed as:

$$\mathbf{Z}_{2k} = \mathrm{Rot}(\mathbf{Z}_{1k}, \theta_{1k}).\mathrm{Rot}(\mathbf{X}_{2k}, \alpha).\mathbf{Z}_{1k} \tag{2}$$

$$\mathbf{Z}_{3k} = \mathrm{Rot}(\mathbf{Z}_{1k}, \psi).\mathrm{Rot}(\mathbf{X}, \theta).\mathrm{Rot}(\mathbf{Z}_E, \varphi).\mathrm{Rot}^{-1}(\mathbf{X}_{3k}, -\gamma).\mathbf{Z}_{1k} \tag{3}$$

The $\mathbf{Z}_E$ platform axis is described by the three ZXZ-Euler angles, ψ, θ and φ. θ_{1k}, θ_{2k} and θ_{3k} are, respectively, the revolute joint variables of the leg k ($k = A, B$ and C). The axes $\mathbf{X}_{2k}$ and $\mathbf{X}_{3k}$ are given, respectively, by $\mathbf{X}_{2k} = \mathbf{Z}_{1k} \times \mathbf{Z}_{2k}$ and $\mathbf{X}_{3k} = \mathbf{Z}_{2k} \times \mathbf{Z}_{3k}$.

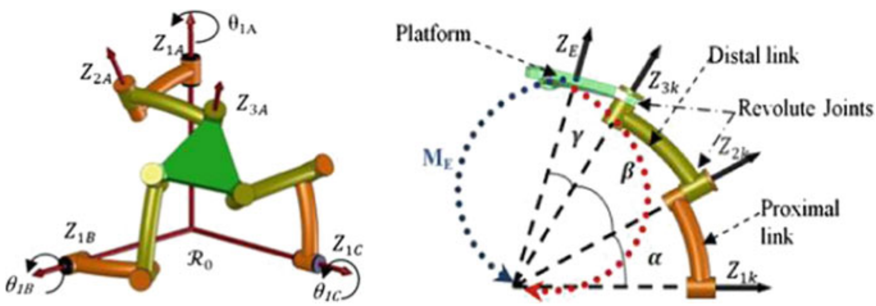

Fig. 2 Architecture and parameters of the SPM. *Left*: SPM architecture. *Right*: one leg parameters

The set of three equations resulting from applying Eq. (1) for the three legs of the mechanism combines the joints parameters $[\theta_{1A}, \theta_{1B}, \theta_{1C}]$ and the platform orientation parameters $[\psi, \theta, \phi]$. Thus, it can be used to detail and solve both the forward and the inverse displacement problems. The inverse kinematics model can be described by the following three equations:

$$A_i cos(\theta_{1k}) + B_i sin(\theta_{1k}) + C_i = \mathbf{0} \tag{4}$$

With $k \in (A, B, C)$ and $i \in (1, 2, 3)$

3 Deterministic Optimization

Chaker et al. [4] presented a detailed approach for the synthesis of an SPM for a surgery application based on GA. Two criteria were minimized. The first one is the workspace that still contains a prescribed workspace. The second one is the the dexterity. The design vector contains the geometric parameters of the mechanism $\mathbf{V} = [\alpha, \beta, \gamma]$ and the optimization problem is expressed as follows:

$$\begin{cases} \text{Minimize } F_1 + F_2 + F_3 \\ F_2 = \sum\limits_{i=0}^{n} \sum\limits_{i=0}^{3} \frac{C_i^2(p_j)}{(A_i^2(p_j)+B_i^2(p_j))} \\ F_3 = \sum\limits_{i=0}^{n} \sum\limits_{i=0}^{3} K(P_j) \\ \text{Subject to } \frac{C_i^2(p_j)}{(A_i^2(p_j)+B_i^2(p_j))} \leq 1 \end{cases} \tag{5}$$

n the number of chosen 'points' on the cone P_j. F_1 is a penalty function that handles the constraints. $F_1 = 0$ means that all the points, defining the desired volume, are contained within the workspace of the SPM. K is the condition number of the Jacobean matrix, which represents the dexterity of the SPM. F_2 represents the sum of the distances of all the points of the manipulator workspace to the cone boundary and F_3 is the sum of the dexterity of the manipulator over its workspace. The desired workspace is represented by a set of orientations P_j within a cone (Fig. 3 (left)). Each point P_j has to be included in the manipulator workspace.

The design vector resulting from this procedure is $\mathbf{V} = [39.4°, 34.1°, 18.2°]$. Figure 3 presents, respectively, the workspace (center) and the dexterity distribution in (ψ, θ) frame (right) of the resulting manipulator. The self-rotation is fixed to 18° and a security angle of 4° was adopted to guarantee that the prescribed workspace can be reached by the end-effector of the mechanism.

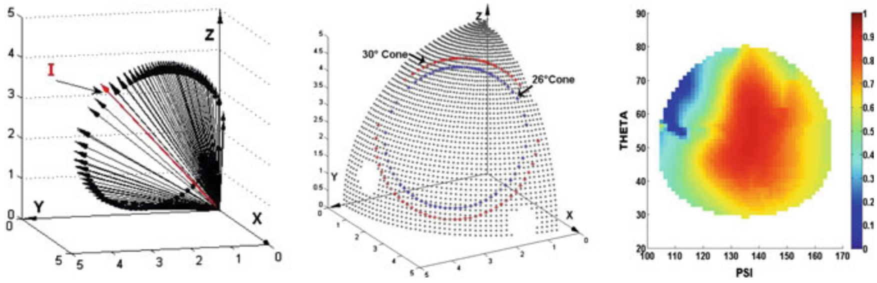

Fig. 3 Architecture and parameters of the SPM. *Left*: prescribed Workspace Model. *Center*: workspace of resulting mechanism. *Right*: dexterity of the resulting mechanism

4 Effects of Manufacturing Errors on the Workspace and the Dexterity

In order to investigate the results of the deterministic optimization, we studied the behavior of the SPM subject to manufacturing errors. For this purpose, we generated a normal distribution with a mean value equal to the nominal design vector resulting from the deterministic optimization. A standard deviation of 5% is imposed. Figure 4a represents the variation of the workspace of the mechanism due to the possible manufacturing errors applied to the design parameters. Three cases are shown: the workspace corresponding to nominal values of the DP, the smallest workspace and the biggest one generated when applying errors on the DP corresponding to the minimal and maximal values of the DP, respectively. We note that the smallest workspace still contains the prescribed workspace. The choice of a security angle is then justified. However, considering the dexterity, the performances of the manipulator are highly variable and it drops to very low values. Figure 4 represents the dexterity of the manipulators with minimal (b), nominal (c) and maximal (d) DP, respectively.

5 Robust Synthesis: Combined GA-MCS

As mentioned before, dexterity showed a high sensitivity toward manufacturing errors. Thus, adopting the results of the deterministic optimization can lead to erroneous results. This issue is treated by the proposed approach for the synthesis of the SPM that combines GA and MCS method [6]. The idea is to take advantages of the GA particularly the wide range of research intervals for DP and multjobiective problem resolution. On the same time, a local evaluation of the behavior of every manipulator toward uncertainty and manufacturing errors is led by the MCS. The optimization problem is then formulated as follows:

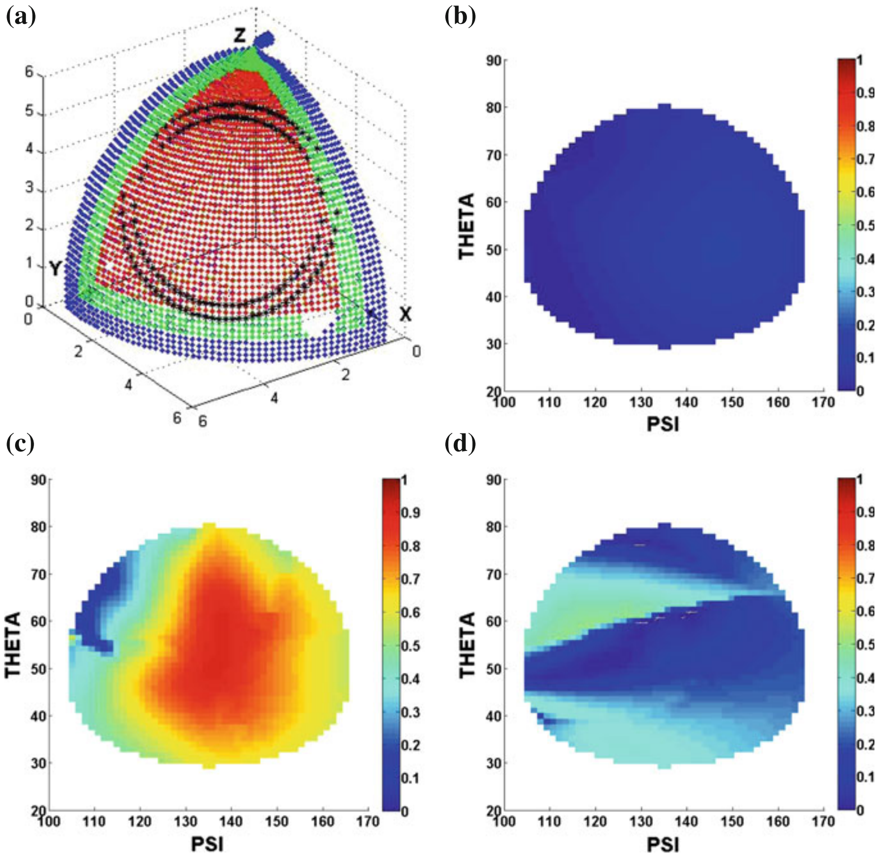

Fig. 4 Manipulator sensitivity to manufacturing error. **a** Workspace variation. **b** Dexterity of manipulator with minimal design parameters. **c** Dexterity of manipulator with nominal design parameters. **d** Dexterity of manipulator with maximal design parameters

$$\begin{cases} \text{Minimize } F_2 \\ \text{Minimize } \bar{F_3} \\ \text{Minimize } \sigma_{F_3} \\ \text{Subject to } \frac{C_i^2(p_j)}{(A_i^2(p_j)+B_i^2(p_j))} \leq 1 \end{cases} \tag{6}$$

Where $\bar{F_3}$ and σ_{F_3} are respectively the mean and the standard deviation of the objective function of the dexterity.

Figure 5 depicts the flow chart of the algorithm. For each iteration of non-dominated solutions, during the evaluation stage, the GA sends a generation of solutions to the MCS [7]. The MCS generates a normal distribution and performs N random simulations for every solution. The first objective function value F_2 is

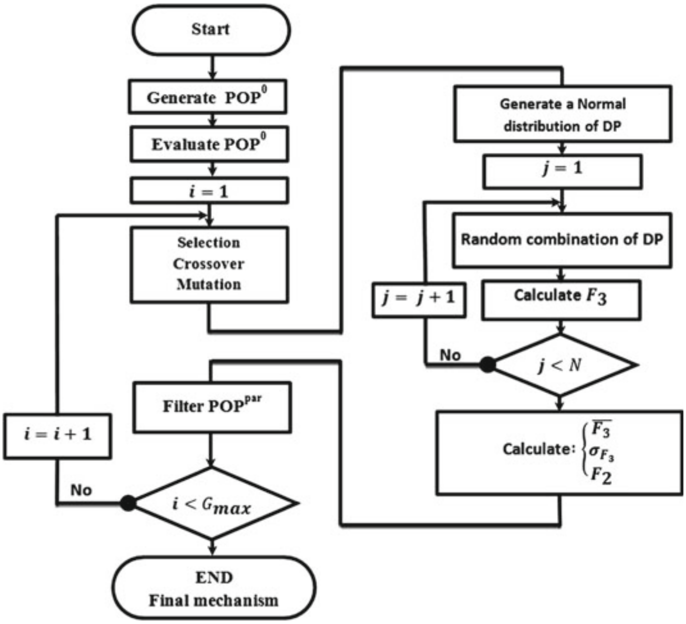

Fig. 5 The GA-MCS flow chart

calculated only for the nominal values of the DP. The output of the MCS is then the value of F_2, the mean value $\bar{F}_3$ and the standard deviation σ_{F_3}. The nondominated solutions undergo the selection, crossover, mutation and reinsertion operations. The MCS number of simulations is $N = 10^3$.

POP^0 is the initial population of the initial design vector (population) to be evaluated and POP^{par} is the Paretian (non-dominated) population.

6 Results and Discussion

The implementation of the Robust algorithm for the synthesis of an SPM led to the following design vector: $\mathbf{V} = [35.2°, 32.9°, 22°]$. Figure 6 shows that the workspace presented in Fig. 6a satisfies the experimental workspace of 26° and the values of the dexterity are kept relatively high with a minimum value of 0.5.

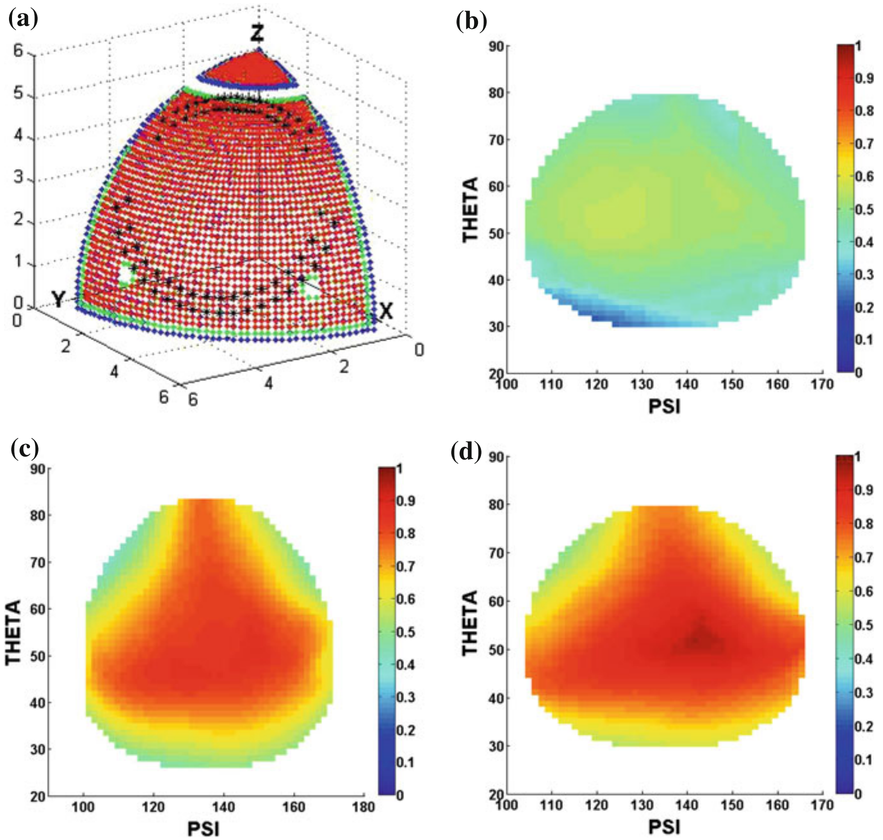

Fig. 6 Performances of mechanism generated by the Robust Synthesis. **a** Workspace variation. **b** Dexterity of manipulator with minimal design parameters. **c** Dexterity of manipulator with nominal design parameters. **d** Dexterity of manipulator with maximal design parameters

7 Conclusion

A multiobjective robust Synthesis strategy for the design of the SPM for dexterous surgery application was presented in this paper. The kinematics of the mechanism was revisited and the effects of manufacturing errors on its workspace and dexterity were studied. This study was based on the results of deterministic optimization elaborated in a previous work. We noted that the dexterity is very sensitive to these errors. Thus, an approach, based on a combined GA-MCS, is proposed to take into account the manufacturing errors in the optimization of the SPM. We are led then to minimize the mean value and the standard deviation of the dexterity. An SPM with low-sensitive dexterity to manufacturing errors is finally presented as a result of this robust algorithm.

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