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Design optimization of a parallel manipulator for otological surgery

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Abstract— **The use of an endoscope in otological surgery as compared to using a microscope provides many benefits in terms of visibility and access to the operating region. The disadvantage of using an endoscope is that it has to be handled by the surgeon during the surgery. A novel parallel kinematic mechanism has been proposed recently for manipulating the endoscope during surgery. This paper details the design requirements considered for the optimization of the process, after consulting surgeons with various expertise. The paper further presents the different evaluation strategies that can be used to optimize the design parameters as per the needs of the application. The contribution of the presented work is the implementation of the surgeons' requirements into an objective function and the optimization of a proposed architecture of a parallel kinematic mechanism suitable for otological surgery.**

I. INTRODUCTION

The use of an endoscope in otological surgery provides many benefits in terms of visibility and access to the operating region (refer to Fig. 2) but, it needs to be handled by the surgeon all the time as illustrated in Fig. 1. This makes the endoscopic surgeries cumbersome, as the surgeon has to switch between tools to operate and manage bleeding in the ear. The incapability of using both hands for the surgery leads to frustration and fatigue of the surgeon. The use of a robot arm to manipulate the endoscope as needed can improve the performance of otological surgeries remarkably. Using assistive systems can result in a drastic reduction in the operating time and positively affect both, the surgeon and the patient. The implementation of robots in inner ear surgery [2] and middle ear surgery [10], [4] were discussed in detail in [12]. Some of them provide a complete solution for robotic surgery, while some can be used as an assistant for the surgeon. The robots in surgery can be used to replace tasks of the surgeon that are mandatory but demand no human expertise. One of the applications in this area is the use of endoscopes in otological surgeries. Previously, robot mechanisms with a serial architecture were proposed as a solution for the endoscopic surgery [10] and the clinical report regarding the same has been published recently [13]. The serial manipulators have a larger workspace in contrast to their parallel counterparts and are relatively easier to design and analyze. That being said, parallel manipulators are generally known for their stiffer structure and are kinematically more robust (see [6] for a recent survey). This can be attributed to the reason that the error in joints is cumulative in serial mechanisms. It is easier to have a fixed center of rotation in a parallel mechanism by the virtue of its architecture and the joint selection. These inherent advantages of parallel mechanisms give them a considerable edge in the application of endoscope manipulation.

The study of the workspace for an otological surgery has been extensively done [8], [9] allowing a better understanding of the intricacies to be taken care of while proposing a mechanism. A 2-dof orientation parallel mechanism with a remote center of motion, 2-U$\underline{P}$S + 1U [7] is analyzed for manipulating the endoscope. The presented work implements an optimization algorithm that combines a local search algorithm with global search methodologies for a faster and more efficient travel in the optimization space [11]. The algorithm is well suited for adapting to different constraints and non-smooth objective function, allowing one to design several evaluation strategies for the design optimization.

This paper explains the technical requirements, constraints, and optimization process for a proposed mechanism for otological surgery. We highlight the various design considerations and their priority elicited from the feedback collected from surgeons in multiple cities with varying experiences. We also present the methodology to include them in the evaluation of the objective function in the optimization problem. The results from different rewarding strategies is presented, allowing one to choose the design parameters depending on the priorities of the surgeons. The possibility of reducing the parameter space in order to have a simpler optimization problem is briefly highlighted in the work. The final contribution is a set of proposed design parameters of the mechanism optimized for the global conditioning index using different strategies that are suitable to implement in an otological surgery.

II. DESIGN REQUIREMENTS AND OPTIMIZATION

In this section, we discuss the design requirements compiled after taking feedback from surgeons, all over France across all expertise levels. This helps in getting the right

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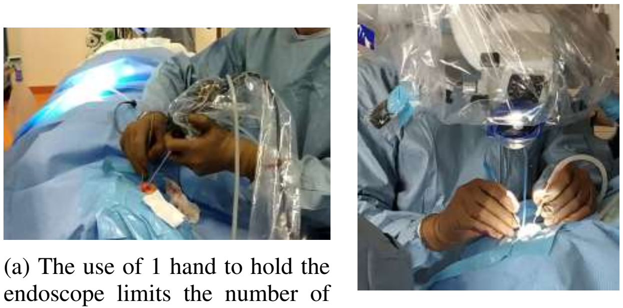
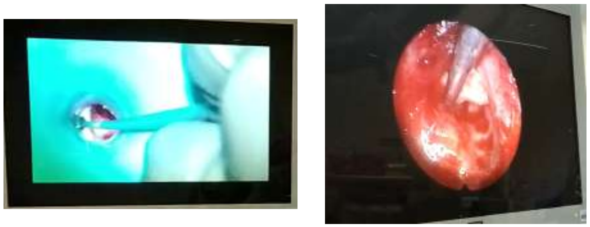


(a) The use of 1 hand to hold the endoscope limits the number of instruments

(b) Surgeon using 2 instruments

Fig. 1: The comparison of the number of instruments possible while using an endoscope and a microscope.



(a) View of the operating area in a microscope

(b) View of the operating area in an endoscope

Fig. 2: The comparison of the view and proximity to operation while using an endoscope and a microscope

parameters and weightages for the objective function to optimize. Later, the optimization strategies and their purpose are explained to motivate the possibility of different optimized designs for a surgery.

A. USER CENTRIC CHOICES

In this section, we discuss the different choices considered while proposing an optimum design. Taking into account the application in our case, it is of prime importance that the feedback from surgeons is analyzed in order to tweak the requirements and solutions related to them. We created a questionnaire in order to understand the requirements and expectations of the mechanism by the surgeons. The questionnaire was designed in two stages. In the first stage, a few preliminary questions were asked that could relate the answers to the desired speed of the actuator as well as their accuracy. A 3D CAD model was designed in order to compare the size of the mechanism with respect to the workspace of the ear as well as the sinus. To familiarize the surgeons with the speed of the mechanism, we prepared simulations of the movement and asked the surgeons to rate them as fast, slow or adequate. The questionnaire also presented an option to prioritize between four requirements; (i) speed of the mechanism, (ii) size of the mechanism, (iii) ease of operation, and (iv) multiple operation capacity. The results of the feedback are presented in Tab. I. It was helpful to get a rough idea of what surgeons perceived when they were presented with the idea of robotic assistance. In the first phase, the participants were limited to one hospital (Centre Hospitalier Universitaire, Nantes) only and no information regarding their level of expertise was taken into account.

	Expertise level		
	High	Medium	New
Priority 1	Easy to use	Easy to use	Compact size
Priority 2	Compact size	Compact size	Easy to use
Priority 3	Speed	Speed	Multipurpose
Priority 4	Multipurpose	Multipurpose	Speed

TABLE I: Priorities of surgeons of various expertise

To get better insights, we designed an advanced questionnaire with an understanding of the surgeons' perspective. As we learned that the surgeons prioritized the ease of use over other parameters, we implemented the System Usability Scale (SUS), the most widely used standardized questionnaire for the assessment of perceived usability and learnability [3]. The information regarding the expertise and years of practice with and without endoscope was also collected. This was important as for a technology to be accepted in the environment, it is important to measure the comfort of adapting to such mechanisms. It also allowed us to have weighted feedback in order to design a mechanism for future operations. The complete environment was created on the CAD model for better perception of the size of the mechanism.

This questionnaire was also shared with a larger group of surgeons from various regions of France[1] in order to get a conclusive idea of the speed, size, and accuracy required for proposing a solution. The feedback from these questions provides a strong foundation for the optimization problem where the optimized solution completely depends on the constraints which are governed by the requirements of the surgeons. [1]

B. OPTIMIZATION STRATEGIES

The mechanism was optimized by implementing combined local and global search strategies using the Nelder-Mead methodology and a low discrepancy sequence. The complete algorithm is presented in [11]. The schematic of the mechanism is given in Fig. 3. The workspace of the mechanism is defined with parameters α and β such that the orientation of the endoscope is given by rotations about the axes of the universal joint by α and β respectively. The mechanism was optimized for global conditioning index (κ_g^{-1}) over the desired Regular Dextrous Workspace (RDW$_d$) of a circle of radius 1 centered at (0, 0) in the workspace. The first joints in leg 1 and leg 2 with respect to the base can be given as:

$$A_1 = \begin{bmatrix} a_1 \cos\phi_1 \\ a_1 \sin\phi_1 \\ h_1 \end{bmatrix}, A_2 = \begin{bmatrix} a_2 \cos\phi_2 \\ a_2 \sin\phi_2 \\ h_2 \end{bmatrix}$$

where, a_i is the distance of the first joint of i^{th} a leg from the origin of the base frame and ϕ_1 is the angle between the xy-projection of a vector from the origin of the base frame to

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[1] The feedback form was shared across all the public hospitals (CHU) of France. and the answers were received anonymously

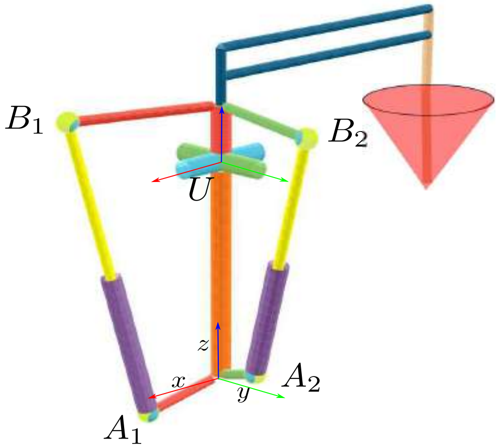

Fig. 3: The parameters to be optimized in 2UPS-1U

Parameters	Value	Parameters	Value
optimization dimension	13	Range of a_i	[0.25, 1.5]
Range of b_i	[0.25, 2]	Range of ϕ_i and ψ_i	[-1.745, 1.745]
Range of h_i	[-0.1, 0.1]	Range of t	[1, 4]
Number of starts	200	Number of iterations	10 and 20
Objective choice	GCI	reward strategy	binary, biased,minimum quality
Range of b_i	[0.25, 2]	Range of ϕ_i and ψ_i	[-1.745, 1.745]
Workspace (in roll and pitch)	circle of radius 1	stroke ratio	1.5
limits on spherical joints	$\pm\pi/6 radians$	Collision constraint	considered

TABLE II: Parameter ranges and other optimization variables

the joint and the x-axis. Similarly, ϕ_2 is the angle between the xy-projection of a vector from the origin of the base frame to the joint and the y-axis. The joints of each leg are at height h_1 and, h_2 respectively. The universal joint (U) in the motion constraint generator leg is given as $[0,0,t]^T$ with respect to the base frame. The spherical joints in each leg are represented with respect to a frame with U as its origin and are given as:

$$B_1 = \begin{bmatrix} b_1 \cos\psi_1 \\ b_1 \sin\psi_1 \\ h_3 + t \end{bmatrix}, B_2 = \begin{bmatrix} b_2 \cos\psi_2 \\ b_2 \sin\psi_2 \\ h_4 + t \end{bmatrix}$$

where, b_i and ψ_i are used to express the spherical joints in the legs and have a similar interpretation as that of a_i and ϕ_i. The joints of each leg are at height $h_3 + t$ and, $h_4 + t$ respectively. Thus, the mechanism can be parameterized by 13 parameters after assuming that the motion constraint generator lies on the z-axis of the base. The 13 mechanism parameters to be optimized, as shown in figure 3 and detailed above, are: $[a_1, \phi_1, h_1, b_1, \psi_1, h_2, a_2, \phi_2, h_3, b_2, \psi_2, h_4, t]$. The optimal parameters and the constraints along with their range are shown in Table II.

1) Evaluation criteria - global kinematic quality: The conditioning number (κ) was introduced in [5] to quantify the quality of motion. It is defined as the value of the asymptotic worst-case relative change in the output for a relative change in the input, and is used to measure how sensitive the output is to changes in the input. The geometrical interpretation of κ is the quantity proportional to the eccentricity of the ellipsoid, giving information about the ease of travel in a particular direction from a current end effector pose. When the κ is equal to 1, we have a sphere, and it corresponds to an *isotropic configuration*. The value of κ ranges from 1 to ∞ and so its inverse, κ^{-1}, is used for bounded values and is given by (1), where σ are the singular values of the Jacobian matrix, $\mathbf{J}$.

$$\kappa^{-1} = \frac{\sigma_{min}}{\sigma_{max}}, \quad \kappa^{-1} \in [0,1] \tag{1}$$

The conditioning number suffers from dimensional non-homogeneity of the Jacobian matrix and is not suitable for manipulators with both translational and rotational movements [1]. As the proposed mechanism has only rotational degrees of freedom (dof), the inverse of the conditioning number is chosen as the quality index. A κ_g^{-1} (GCI), the mean of summation of the values of quality index (κ^{-1}) over the discretized RDW$_d$, is defined as follows,

$$\kappa_g^{-1} := \frac{\sum_1^n \kappa^{-1}}{n}, \text{n : discretized points in RDW}_d \tag{2}$$

2) Rewarding strategies : Binary and center-biased reward: As we explore the possibility of having a large workspace with the proposed mechanism, it was decided to first see the results for maximizing the feasible workspace only. This is done by the binary reward strategy. Each configuration is awarded either 1 or 0 depending upon the point respecting the passive joint limits and the actuator limits only as shown in Fig. 4. The constraints for non-singular points and collision are treated more strictly. If any configuration in the RDW$_d$ is singular or does not respect the collision constraint, then the evaluation is given a very large penalty. This makes sure that no matter how big the feasible workspace is, it is disqualified as a valid solution if it contains any singular curve or colliding configurations. As the endoscope mostly stays in the center of the RDW$_d$, a center-biased strategy can be implemented to have better kinematic performances in and around the center of the feasible workspace. One of such ideas is illustrated in Fig. 5. In this strategy, the area that respects all the constraints in the RDW$_d$ is rewarded inversely proportionate to its proximity to the center of the workspace. It is expected to have designs that may have poor kinematic quality near the boundary of the workspace, but have excellent control in the area where the endoscope will be operational for most of the time.

3) Rewarding strategies: minimum quality: It is desirable to have a manipulator which has the capability to move in any direction with equal agility in any configuration of the feasible workspace. It was observed that the workspace is mainly bound by the singularity curves and as we go near singular configurations, the determinant of the Jacobian matrix drops drastically in value. As the global kinematic quality depends on the singular values of the Jacobian matrix, it becomes harder to have dextrous mobility near singular boundaries. So, a constraint is necessary to place a minimum value of the quality index in a particular workspace that will be used very often. This also allows us a buffer to controllably stop the manipulator if it shoots away from this prescribed working area. We bound the quality with acceptable ranges in the 64% of the RDW$_d$. So, the quality

Parameters	Binary reward	Center-biased reward	Minimum quality reward
Best point $[a_1,\phi_1,h_1,b_1,\psi_1,h_2,a_2,\phi_2,\ h_3,b_2,\psi_2,h_4,t]$ (refer figure 3)	[0.375, -1.75, 0.07, 1.23, 1.26,-0.15, 0.75, -0.79, -0.06, 1.17, -0.24, 0.19, 3.17]	[0.96, -1.38, 0.08, 1, -0.96, -0.14, 0.82, 0.04, -0.05, 1, 0.6, 0, 2.97]	[0.9, -0.51, 0.01, 0.71, -0.55, 0.08, 1.07, -0.14, -0.02, 0.7, 0.98, 0.08, 3.26]
Best actuator range	[2.67, 4]	[2.41, 3.62]	[2.75, 4.1]
evaluation	.	.	.
mean	0.76	0.76	0.78
standard deviation	0.18	0.20	0.17
maximum evaluation	1	1	1
configuration ($[\alpha,\beta]$)	[0.15, -0.13]	[-0.32, -0.09]	[-0.34, 0.27]
minimum evaluation	0.402	0.16	0.404
configuration ($[\alpha,\beta]$)	[-0.66, -0.75]	[0.94, 0.34]	[0.84, -0.54]

TABLE III: The results for the optimization of 2-dof RCM mechanism

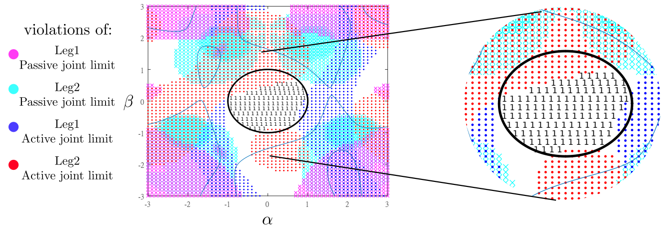

Fig. 4: Binary reward strategy

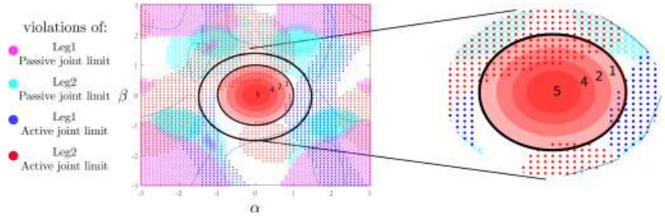

Fig. 5: Center biased reward strategy: the feasible points near the center of RDW$_d$ are given higher weightage

of the manipulator is treated as a constraint in this box and rewarded with either binary or biased rewards outside the inner box. The concept is graphically represented in Fig. 6.

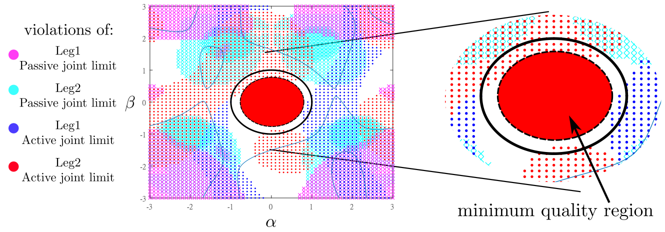

Fig. 6: The minimum quality rewarding strategy

III. RESULTS

The results obtained following the application of each strategy proposed in the previous section are shown in III. The binary rewarding strategy is a basic evaluation criterion, and it can be seen from Fig. 7 that the feasible workspace is indeed limited. In the center-biased strategy (refer to Fig. 8), the kinematic quality index is at the highest in the center but has poor quality around the boundary of the desired workspace. The most successful strategy that satisfies the requirements of the surgeons as well as has good kinematic performance in the major area of the desired workspace is the minimum quality strategy as illustrated in Fig. 9.

IV. CONCLUSIONS

The presented work details the different priorities of surgeons to be considered while designing a mechanism for otological surgery. The work also details the optimization method as well as the different strategies implemented in order to have better kinematic properties in the feasible workspace of the manipulator.

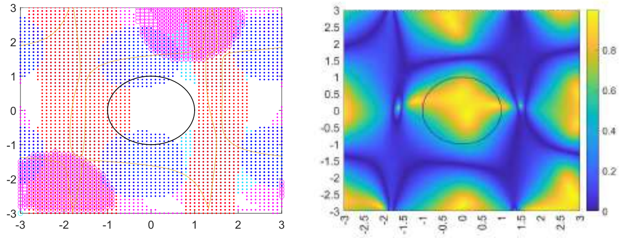

Fig. 7: The feasible workspace (white space) and the heatmap for the quality index with binary rewarding strategy

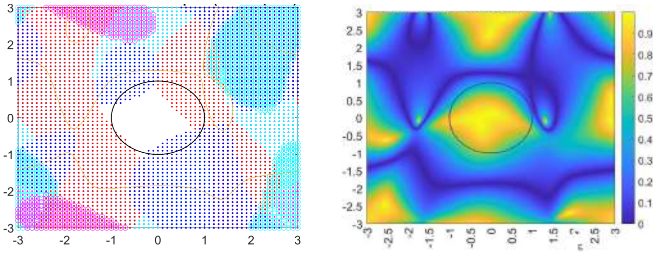

Fig. 8: The feasible workspace (white space) and the heatmap for the quality index with center biased rewarding strategy

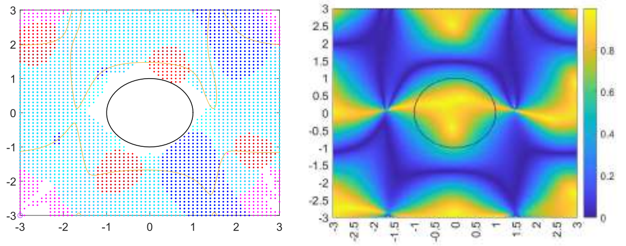

Fig. 9: The feasible workspace (white space) and the heatmap for the quality index with minimum quality rewarding strategy

The contribution of the work is presented as a result of a set of design parameters for an optimized 2U$\underline{P}$S + 1U mechanism using each presented reward strategy, allowing the designer to choose the dimensions as per the requirement.

The future work is to analyze the impact of simplification of design parameters, to obtain easy to manufacture designs, on the optimization process. Also, a physical prototype is in progress to further measure the impact of the feedback quantitatively as well as qualitatively and to validate the design requirements with the surgeons.

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