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Towards an Automated and Optimal Design of Parallel Manipulators

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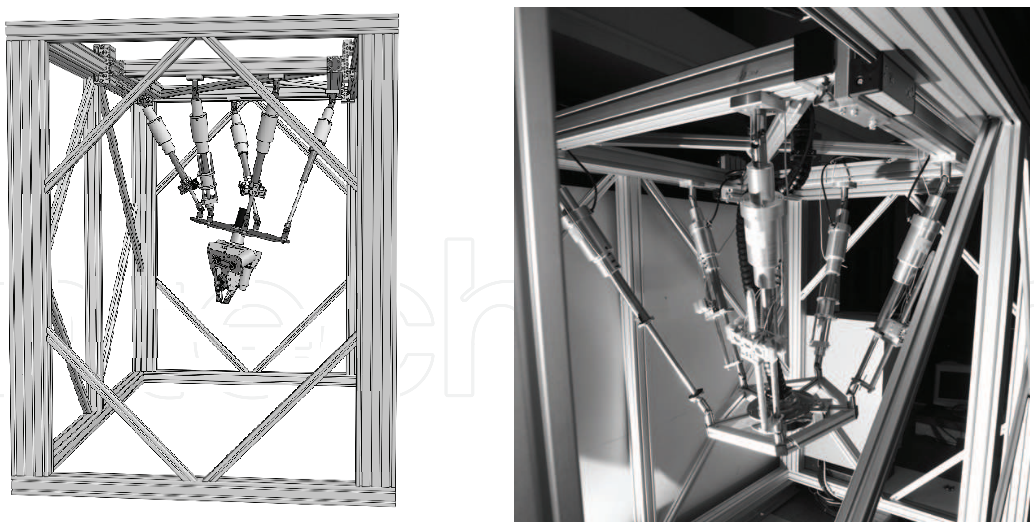
1. Introduction

The development of parallel manipulators involves new challenges related to the design of the mechanical, actuating and information-processing subsystems. In this chapter, we limit ourselves to the design of the mechanical subsystem. It typically includes a structural and a dimensional synthesis. Whereas the first one consists in finding the *a priori* most appropriate mechanical architecture, i.e. the types and the arrangements of the joints and the links that make up the robot, the latter deals with the determination of its dimensions in order to match the requirements of the task at hand as closely as possible. Structural synthesis may be achieved either by combining in a systematic way the different types of joints and links allowed by the task in order to obtain all possible arrangements, or by considering pre-existing solutions and customizing them. Clearly, this step relies on engineers' intuition, whereas dimensional synthesis can more easily be automated. Still, it remains a very delicate task, especially for parallel manipulators. Indeed, the performances of these manipulators heavily depend on the chosen geometry. As underlined by many authors (Gosselin, 1988; Merlet, 2006), they also possess kinematic features that vary in opposite directions when their dimensions are modified. In this chapter, we propose an approach to the optimal design of parallel manipulators that helps the designer to find the appropriate dimensions of the mechanical structure he has opted for. For the sake of clarity, we illustrate our approach by a practical example: the design of a guidance mechanism to be used in a stitching unit.
This challenging task results from the continuous demand for speeding up the assembly process of reinforcement textiles needed for the manufacture of fibre composites This demand has led to an increased automation over the last decade in the textile industry. In order to reduce the process duration and to improve both the productivity and the quality of the assembly seam, robot stitching units have been introduced. Recently, we have proposed a new sewing technology in (Kordi *et al.*, 2006). In contrast to conventional ones, all mechanical parts of the proposed sewing head are arranged only on one side of the work pieces. This enhances chances for the automation of the assembly process, as the free side can be more easily attached to manipulators. The next step is to design an appropriate manipulator that takes into consideration the peculiarities of this technology.



(a) (b)

Fig.1 Perspective view of the CAD model (a) The stitching unit (b)

We have already established a systematic procedure for the generation of all the structures having the number of degrees of freedom required by the task. We have also defined a list of evaluation criteria to asses the generated architectures. Without being exhaustive about this methodology, we show a CAD model of the resulting mechanical structure in figure 1a: a hybrid manipulator with seven degrees of freedom. Figure 1b depicts the finished stitching unit. It consists of a fully parallel robot with five degrees of freedom (Mbarek *et.al*, 2005), whose moving platform is equipped with a drive that amplifies the rotation of the sewing head about its longitudinal axis. This large rotation is required for tracking circular seam paths. Furthermore, this unit is mounted on a linear axis to achieve large translations in one direction. The development of such a stitching unit implies a careful design of the parallel manipulator to be used. Indeed, its kinematic performances will be decisive for the overall performances of the stitching unit.

So far, we have only considered the number of degrees of freedom. Further stages of the design process have to involve other requirements such as the workspace volume, the positioning accuracy of the sewing head, its maximal translation and angular velocities etc…. To this end, we first review some available design methodologies for parallel manipulators. Then, we investigate the kinematic and Jacobian analysis of the parallel manipulator to be considered. In the fourth section, we list the requirements of the task and associate to each of them a performance index that indicates whether the requirement is satisfied by the manipulator or not. Once these performance indices can be evaluated numerically, we will develop a numerical procedure that guarantees the generation of design solutions that meet all prescribed requirements simultaneously. Finally, we will give graphical representations of the prescribed performances and the obtained ones.

2. Available design methodologies

Many approaches have already been proposed in a rich literature about the design of parallel robots. The parameter space approach has often been proposed by Merlet (Merlet, 1997; Merlet, 2006). It consists in finding sets of robot geometries by considering successively two requirements, i.e. the workspace requirement and the articular velocities. The intersection of these sets defines all designs that satisfy these two requirements simultaneously. The obtained set of design solutions is then sampled to determine the best compromise with regard to other requirements, which were not considered yet. An implementation of the parameter space approach based on interval analysis has also been proposed in (Merlet, 2005a; Hao and Merlet, 2005). Interval analysis has appealing advantages, such as generating certified solutions and finding all possible mechanisms for a given list of design requirements. Yet, it remains very time consuming and requires a lot of storage. It should be pointed out, however, that some improvements can speed up the algorithm, see (Merlet, 2005b).

Another way to deal with the optimal design of parallel robots is the cost function approach. Some authors focused on the synthesis of parallel manipulators whose workspace complies as closely as possible with a prescribed one (Gosselin and Boudreau, 2001; Ottaviano and Ceccarelli, 2001). Later, the design problem becomes a multi objective optimisation problem (Ceccarelli, 2002; Arsenault and Boudreau, 2006). Many of these formulations have, however, the drawback of providing one design solution, which is generally a trade off between the design objectives. Having one design solution may confine the end user at many stages of the design process. In our formulation, we will define lower bounds for each performance. If a robot features kinematic characteristics that are better than the prescribed ones, then it will be retained. Hence, many design solutions are possible. Furthermore, if these bounds are chosen adequately, the proposed formulation ensures the generation of many solutions that satisfy all prescribed requirements. Our formulation can, therefore, be seen as an alternative between the parameter space approach that provides a set of infinite solutions and usual formulations that find one design solution.

3. Jacobian analysis

Prior to the quantification of the manipulator's kinematic performances, we review its kinematics without being exhaustive, for more details see (Mbarek *et.al*, 2005). As depicted in figure 2, the parallel manipulator consists of five kinematic chains. Four of them have the same topology and are composed of a universal joint on the base, a moving link, an actuated prismatic joint, a second moving link and a spherical joint attached to the platform. In reality, universal joints have also been used for the platform, since the slider of the actuators can rotate about its longitudinal axis. The fifth kinematic chain can be distinguished by the anti-twist device. This special leg restricts the motion of the platform to five degrees of freedom so that only five of the six Cartesian coordinates can be prescribed independently. The remaining rotational coordinate ψ cannot be controlled; it corresponds to a constrained rotation of the platform due to the special leg. The first step in achieving the kinematic analysis is, therefore, the computation of this angle by considering the supplementary constraint in the special leg.

Referring to figure 1, a vector-loop equation can be written for the ith leg of the mechanism as:

$$\mathbf{p}_i = -\mathbf{a}_i + \mathbf{r} + \mathbf{Q}\mathbf{b}_i^{'} \tag{1}$$

where Q denotes the Euler rotation matrix and pi represents the vector from the joint centre point Ai to the joint centre point Bi. The vector r = (x, y, z)^T designates the position of O′ with respect to the frame of coordinates (O, x, y, z). Furthermore, we denote by a and by b the radii of the base and the platform.

Differentiating (1) with respect to time for each leg leads to six equations that can be written in this form:

$$\dot{\boldsymbol{\rho}} = \mathbf{J}_p \dot{\boldsymbol{\chi}} \tag{2}$$

where $\dot{\boldsymbol{\chi}} = \begin{pmatrix} x & y & z & \omega_x & \omega_y & \omega_z \end{pmatrix}^T$ is the velocity vector of the end effector and $\mathbf{J}_p$ denotes the Jacobian matrix of the parallel manipulator. It has been shown in (Mbarek *et.al*, 2005) that:

$$\mathbf{J}_p = \begin{pmatrix} \mathbf{s}_1^T & \left(\mathbf{Q}\mathbf{b}_1^{'} \times \mathbf{s}_1\right)^T \\ \vdots & \vdots \\ \mathbf{s}_5^T & \left(\mathbf{Q}\mathbf{b}_5^{'} \times \mathbf{s}_5\right)^T \\ \mathbf{0} & \mathbf{s}_5^T \end{pmatrix} \tag{3}$$

The vector $\mathbf{s}_i$ denotes the unit vector along the ith leg. The last row of $\mathbf{J}_p$ corresponds to the additional constraint in the special leg. Hence, the first five elements of the vector $\dot{\boldsymbol{\rho}}$ are the actuators velocities and the sixth element corresponds to the component of the platform's angular velocity along the unit vector s_5. The interrelation between an external wrench **F** exerted on the platform and the vector of the actuators' forces $\boldsymbol{\tau}$ is provided by following equation:

$$\mathbf{F} = \mathbf{J}_p^T \boldsymbol{\tau} \tag{4}$$

The sixth element of the vector $\boldsymbol{\tau}$ corresponds to the moment exerted by the additional constraint.

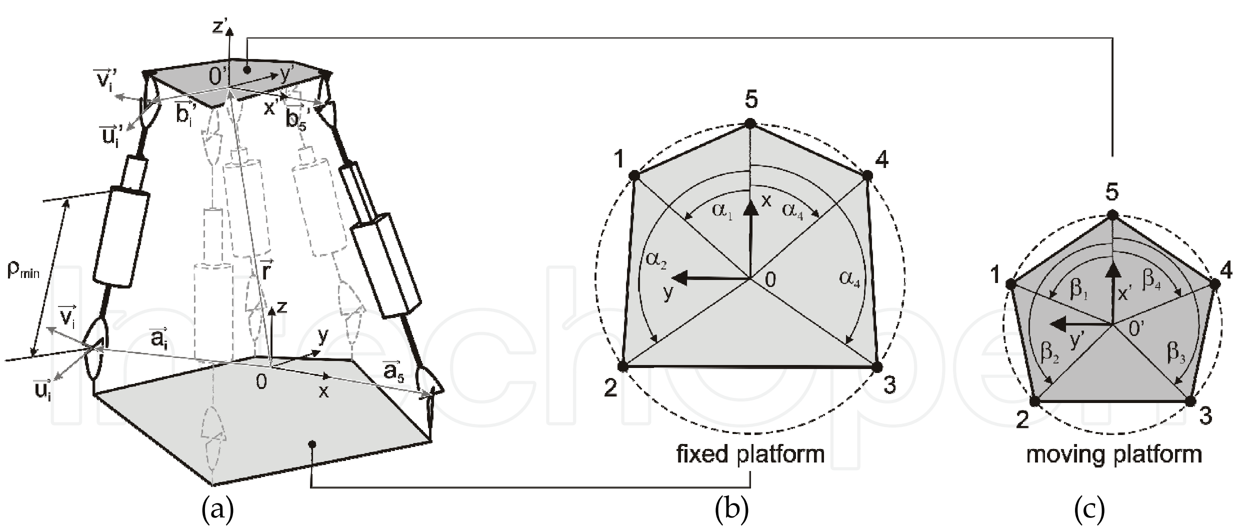


Fig. 2. Schematic representation of the parallel manipulator (a), the base (b) and the platform (c)

3. The design requirements and the optimisation of the robot's performances

The starting point of the design process is usually a list that tabulates the requirements of the task, as shown in table 1. These may be categorized according to their importance as demands or wishes. Whereas demands are those requirements that must be met to obtain a satisfactory design, wishes can be used to make the final choice between different feasible solutions. The corresponding values of the manipulator's performances can be seen as lower bounds to be met. In other words, each manipulator that features at least these values is considered as an appropriate design. In this way, many design solutions can be generated. Besides, the search for an appropriate design is more straightforward.

Requirements of the stitching process			**Performance index**	
Geometry	Size of the work pieces	400 x 400 x 200 mm³	Constant orientation Workspace	400 x 400 x 200 mm³
	Shape of the work pieces	Three-.dimensional	Rotation ranges	±20°
Motion parameters	Stitching speed	1000 stitches per minute	Translation velocity	0.3 m/s
			Angular velocity	π/2 rad/s
Machining quality	Allowed deviation from the desired seam shape	0.1 mm	Positioning accuracy	0.1 mm
			Orientation accuracy	0.05°

Table 1: Requirements list and the corresponding performance indices

As shown in Table 1, we associate to every demand one or more kinematic performances of the manipulator. In the following, we attach an index to each performance in order to quantify to what extent each requirement is satisfied or violated. Once the derived indices can be evaluated numerically, we present a formulation of the optimal design problem able to provide many design solutions that satisfy all demands of the requirements list. Since the corresponding performances of the manipulator may differ from each other in both unit and value, we derive functions whose values range from 0 to 1. 0 indicates that the manipulator satisfies the design criterion. On the other hand, the index converges to 1, if the kinematic performances of the manipulator are far away from the prescribed values.

3.1 The design parameters

Prior to the formulation of the objective functions, we should identify the geometric parameters that have to be modified in order to meet the requirements. Previous works of different research groups showed that the accuracy of parallel manipulators is sensitive to the angles a_i and β_i. Moreover, the radii of the base and the platform, the minimal and maximal leg lengths affect the workspace's volume of the manipulator. We may also assume that the joint centre points A_i and B_i are symmetrically disposed on a circle, i.e. $a_1 = a_4$, $a_2 = a_3$, $\beta_1 = \beta_4$ and $\beta_2 = \beta_3$. The attachment points A_5 and B_5 of the special leg should not be modified. Indeed, a modification of these points complicates the computation of the constrained rotation; and thereby the solution of the inverse kinematic problem. A further design parameter could be the height z_0 of the platform's start position. In this way, we end up with 9 design parameters that can be defined as a vector:

$$\mathbf{\Pi} = \left(\rho_{max} \quad \rho_{min} \quad a_1 \quad a_2 \quad a \quad \beta_1 \quad \beta_2 \quad b \quad z_0\right)$$

3.2 The workspace requirement

The seam path to be achieved should entirely fit in the workspace of the manipulator. As we intend to join small and medium sized fibre composites, the required workspace should be a parallelepiped of 400mm x 400mm x 200mm. In order to join 3D structures of fibre composites, the needles of the sewing head should always be perpendicular to the seam path. Hence, a rotation of the sewing head of 1000 stitches per minute, and thereby of the manipulator's platform should be possible. For every point in this parallelepiped, each leg length $\|\mathbf{p_i}\|$ must neither exceed the maximal available stroke ρ_{max}, nor be lower than a length offset ρ_{min}, which corresponds to the stator length.

Accordingly, the objective function F_1 corresponding to the workspace criterion can be formulated for each ith leg as:

$$\mathbf{F}_{1,i}^{n}(\chi_{n,}\boldsymbol{\pi}) = \begin{cases} 1 - \dfrac{\rho_{\max}}{\|\mathbf{p}_i\|}, & \text{if } \|\mathbf{p}_i\| > \rho_{\max} \\ 0, & \text{if } \rho_{\min} \le \|\mathbf{p}_i\| \le \rho_{\max} \\ 1 - \dfrac{\|\mathbf{p}_i\|}{\rho_{\min}}, & \text{if } \|\mathbf{p}_i\| < \rho_{\min} \end{cases} \tag{5}$$

where $\chi_n = \begin{pmatrix} x_n & y_n & z_n & \varphi_n & \theta_n & \psi_n \end{pmatrix}^T$ represents the vector of the actual pose. The workspace is defined as a set of N finitely separated poses that result from the discretisation of the prescribed parallelepiped. As formulated in (5), the objective function F_1 to be minimized has numerical values between 0 and 1. If the leg length is within the range ρ_{min} and ρ_{max}, the workspace requirement is satisfied and F_1 returns 0. It converges to 1, if the leg length is greater than the maximal stroke ρ_{max} of one actuator or lower than ρ_{min}.

Furthermore, the rotation of the passive joints should not exceed the operating angles for every configuration of the manipulator in the prescribed parallelepiped.

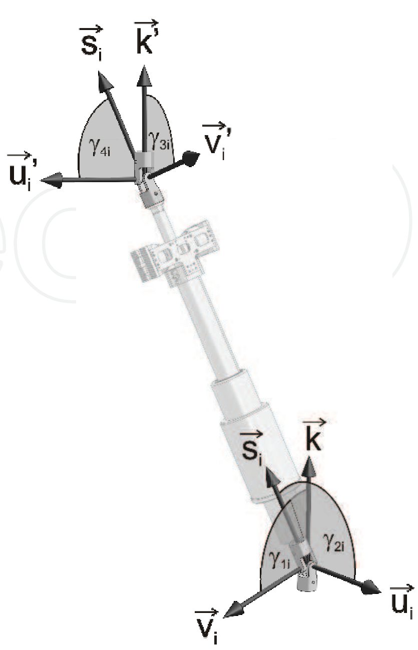


Fig. 3: Operating angles of the universal joints

To this end, the resulting angles in the universal joints on the base and on the platform should be within a range of ±45°. An additional objective function is therefore necessary to guarantee that every configuration in the prescribed workspace is feasible with regard to the passive joints:

$$\mathbf{F}^{n}_{2,ij}(\chi_{n},\boldsymbol{\pi}) = \begin{cases} 1-\left|\dfrac{\gamma_{max}}{\gamma_{ji}}\right|, & \text{if } \gamma_{ji} > \gamma_{max} \\ 0, & \text{if } \gamma_{min} \le \gamma_{ji} \le \gamma_{max} \\ 1-\left|\dfrac{\gamma_{ji}}{\gamma_{min}}\right|, & \text{if } \gamma_{ji} < \gamma_{min} \end{cases} \tag{6}$$

γ_{ji} denotes the rotation angles of the passive joints in each leg. The computation of these angles is straightforward and is not reported in this work.

3.3 The accuracy requirement

Position and orientation errors of the tool centre point are, mainly, due to the bounded resolution of the encoders. The amplification of these errors is given by (8) in each direction of the Cartesian space.

$$\delta\boldsymbol{\rho} = \mathbf{J}_{p}\delta\chi \tag{8}$$

In order to avoid the time consuming inversion of the Jacobian matrix, we specify the desired accuracy of the platform and try to match the known resolution of the encoders, i.e. 10 μm. The minimal position and orientation accuracy should not be lower than 0.1 mm in x, y and z direction and 0.05° for the angles φ and θ.

A possible design objective is therefore the maximization of $\delta\boldsymbol{\rho}$ over the workspace. Hence, the corresponding function can be written as:

$$\mathbf{F}^{n}_{4,i}(\chi_{n},\boldsymbol{\pi}) = \begin{cases} 1-\dfrac{\delta\rho_{i}}{\delta\rho_{min}}, & \text{if } \delta\rho_{i} < \delta\rho_{min} \\ 0, & \text{if } \delta\rho_{i} \ge \delta\rho_{min} \end{cases} \tag{9}$$

3.4 The stiffness requirement

External forces and moments acting on the moving platform cause a compliant displacement that depends on the stiffness of the legs k_1, k_2, k_3, k_4 and k_5 and the additional constraint in the special leg k_6, i.e. the stiffness of the universal joint on the platform. In this work, we are not interested in evaluating the stiffness matrix $K = diag(k_1, k_2, k_3, k_4, k_5, k_6)$. Rather, the parameters $k_1, \ldots, k_6$ correspond to scaling factors. Consequently, the compliant displacements differ from the displacements that may occur in reality. Even though, it's still important to consider this design criterion, since it guarantees that the compliant displacements in each direction are bounded. It should be noted, however, that the parameter k_6 has been chosen larger than the other stiffness parameters.

For a given displacement of the actuators and the constraint in the special leg, the resulting forces in the actuators are

$$\boldsymbol{\tau} = \mathbf{K}\delta\boldsymbol{\rho} \tag{10}$$

After substituting $\boldsymbol{\tau}$ and $\delta\boldsymbol{\rho}$ in (10) by $\mathbf{J}_p^{-T}\mathbf{F}$ and $\mathbf{J}_p\delta\boldsymbol{\chi}$ from (4) and (8), we obtain an interrelation between the external wrench and a compliant displacement:

$$\mathbf{F} = \mathbf{J}_p^T\mathbf{K}\mathbf{J}_p\delta\boldsymbol{\chi} \tag{11}$$

In order to avoid the time consuming inversion of the Jacobian matrix, we specify the minimal external forces and moments in each direction and strive to find design geometries whose compliant displacements are lower than 0.1 mm in each direction and 0.05° about the direction of the reference frame. For simplicity of exposition, we denote by F_{min} both the minimal external forces and moments. The corresponding function can be written as:

$$\mathbf{F}_{5,i}^n(\boldsymbol{\chi}_n, \boldsymbol{\pi}) = \begin{cases} 1 - \dfrac{F_i}{F_{min}}, & \text{if } F_i < F_{min} \\ 0, & \text{if } F_i \geq F_{min} \end{cases} \tag{12}$$

3.5 The velocity requirement

Owing to the fact that actuators velocities are bounded, it is important to find a design that can achieve the required Cartesian velocities throughout the workspace without exceeding the allowable actuators velocities. The velocity transmission relation is given by (2). Clearly, the maximal required velocity in each actuator for a given velocity of the platform is:

$$\dot{\rho}_i = \sum_{i=1}^{6} \left|J_{pij}\right| \dot{\chi} \tag{9}$$

where $\left|J_{pij}\right|$ is the absolute value of the ith row and jth column of the Jacobian. A possible design objective is therefore the minimisation of $\dot{\rho}_i$ over the workspace. In this case, the corresponding function can be written as:

$$F_{6,i}^n(\chi_n, \pi) = \begin{cases} 1 - \dfrac{\dot{\rho}_{max}}{\dot{\rho}_i}, & \text{if } \dot{\rho}_i > \dot{\rho}_{max} \\ 0, & \text{if } \dot{\rho}_i \leq \dot{\rho}_{max} \end{cases} \tag{10}$$

In order to achieve our objective of 1000 stitches per minute, the manipulator's platform should reach a translation velocity of 0.3 m/s in x, y and z direction and an angular velocity of $\pi/2$ rad/s about the y axis for any pose in the prescribed workspace. The actuators velocities $\dot{\rho}_{max}$ should not exceed 1 m/s. Whereas the accuracy requirement consists in maximizing $\delta\rho$, thereby maximizing the components of the Jacobian matrix, the velocity requirement consists in minimizing these components.

3.6 The dexterity criterion

One major drawback of parallel manipulators is singular configurations within the workspace. In these configurations the manipulator gains or looses some degrees of freedom and becomes uncontrollable. Also ill conditioned configurations, i.e. configurations close to a singularity, have to be avoided. Indeed, in these configurations large actuators forces are required to support even reasonable loads. In order to avoid these regions, an upper bound for the condition number of the Jacobian matrix should be specified $\kappa_{\max} = 70$. It should be noted that this criterion can not be associated to an explicit design requirement. The corresponding objective function can be formulated as:

$$\mathbf{F}_{7,i}^{n}\left(\chi_{n,}\boldsymbol{\pi}\right)=\begin{cases}1-\frac{\kappa_{\max}}{\kappa}, & \text{if } \kappa>\kappa_{\max}\\ 0, & \text{if } \kappa\leq\kappa_{\max}\end{cases} \tag{7}$$

The condition number κ is defined as the ratio of the maximal singular value to the minimal singular value of the Jacobian matrix. It can be computed by the Matlab function cond.

4. Results

It's increasingly apparent that minimizing the derived objective functions to 0 throughout the manipulator's workspace yields a manipulator whose geometry satisfies all prescribed requirements. Hence, the optimal design problem can be formulated as:

$$\min_{\pi} \mathbf{F}(\pi)=\min_{\pi}\left[\mathrm{F}_1(\chi_1,\boldsymbol{\pi}),\cdots,\mathrm{F}_1(\chi_N,\boldsymbol{\pi}),\cdots,\mathrm{F}_C(\chi_N,\boldsymbol{\pi})\right] \tag{11}$$

subject to $\boldsymbol{\pi}\in\left[\boldsymbol{\pi}_{\min},\boldsymbol{\pi}_{\max}\right]$

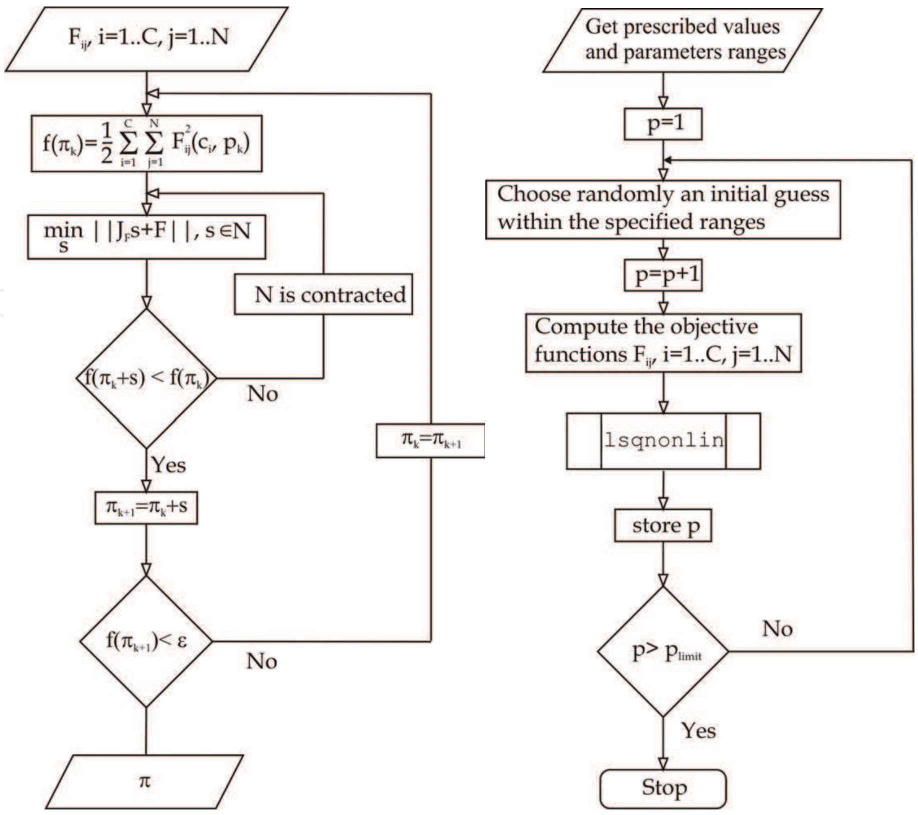
where C denotes the number of the performance indices. Additional constraints for the design parameters have been included to obtain manipulator sizes within practical values. After the formulation of the optimal design problem, we may now derive a numerical procedure to find the optimal design according to the requirements of section 4.

4.1 The numerical procedure

The numerical procedure adopted in this paper is based on trust region methods, as implemented in the Matlab function *lsqnonlin* for large scale optimisation problems , see figure 4.

Basically, an objective function F to be minimized is approximated at each step with a simpler function: $J_F s+F$ in a neighbourhood N of the current point (the trust region). J_F is the Jacobian matrix of the objective function. A trial step s is computed by minimizing the new function over the trust region. If an improvement of the objective function, i.e. a lower function value, is achieved, the current point is updated using the computed step. Otherwise, the current point remains unchanged and the region is contracted, see also (The Math Works Inc., 2006).

In order to generate many design solutions, the final algorithm chooses randomly different initial guesses within the specified ranges of the design parameters, see figure 4. If all objective functions are reduced to 0, the design parameters are stored and another initial guess is selected. We ran this optimization algorithm with p_{limit} = 500 different initial guesses. The computation time was less than 4 hours, and more than 300 feasible design solutions have been found.



(a) (b)

Fig. 4: A flow chart of the MATLAB function lsqnonlin (a) Flow-chart of the overall numerical procedure (b)

Many design solutions are very close to each other and can be gathered in different groups of solutions. Table 2 shows a list of five design solutions sorted into ascending value of the maximal leg length.

ρ_{max} [m]	ρ_{min} [m]	α_1 [°]	α_2 [°]	a [m]	β_1 [°]	β_2 [°]	b[m]	z_0 [m]
1.15	0.67	106	162	0.55	125	151	0.21	0.73
1.3	0.80	109	143	0.57	133	160	0.21	0.87
1.22	0.66	135	148	0.6	127	160	0.17	0.85
1.34	0.83	131	148	0.6	106	168	0.38	0.94

Table 2: Four feasible design solutions

4.2 Simulation results

In this section, we show the simulation results of the first solution of table 2. Figure 5 and 6 depict an isometric view and a view of the x, y plane of both the prescribed and the constant orientation workspace of the selected solution. As shown by figure 7 and 8 an orientation of $\theta = 20°$ is also feasible without violating the workspace requirement.

Figure 9 and 10 depict the displacement of the first actuator for a position error of 0.1 mm in each direction and an orientation error of 0.05° in the two first Euler angles, as defined in (Mbarek et.al, 2005). Moreover, figure 11 and 12 demonstrate that these errors induce a displacement of 1e-4 m

Fig. 4: Flow-chart of the overall numerical procedure

throughout the workspace for $\theta = 20°$. The accuracy requirement is therefore satisfied for this actuator, since the resolution of the encoders is 1e-5 m. For simplicity of exposition, the displacements of the other actuators are not represented in this work.

The velocity requirement is also satisfied. Indeed, the actuators velocities of each actuator is less than the prescribed limit 1 m/s. Figure 13-16, depict the required velocities of the fifth actuator. Finally, figure 17-20 depict the distribution of the condition number throughout the workspace.

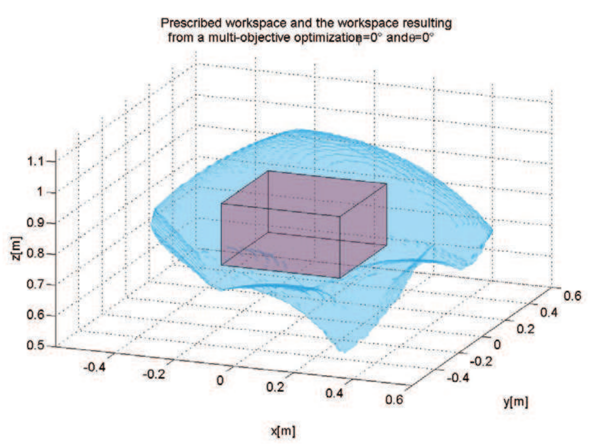


Fig 5: The prescribed workspace and the workspace of the selected design solution for $\varphi = 0, \theta = 0°$

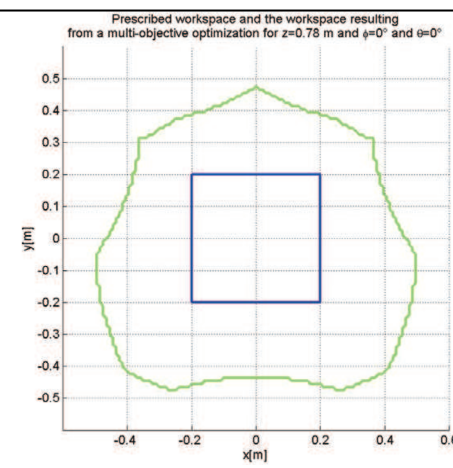


Fig 6: The prescribed workspace and the workspace of the selected design solution for $z = 0.78m, \varphi = 0, \theta = 0°$

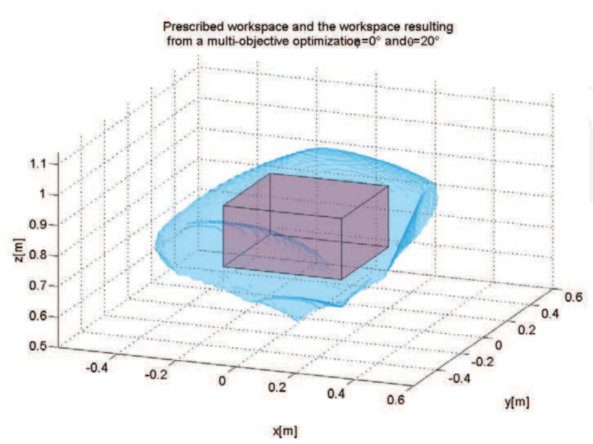


Fig 7: The prescribed workspace and the workspace of the selected design solution for $\varphi = 0, \theta = 20°$

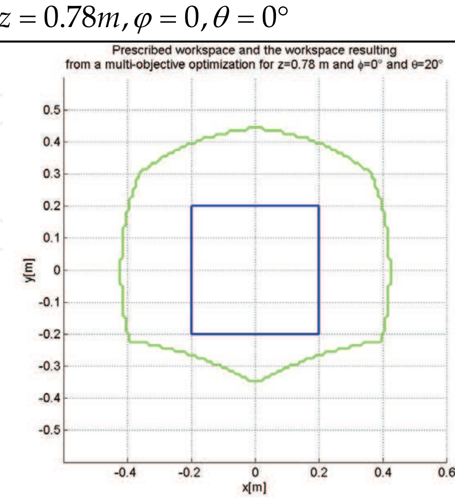


Fig 8: The prescribed workspace and the workspace of the selected design solution for $z = 0.78m, \varphi = 0, \theta = 20°$

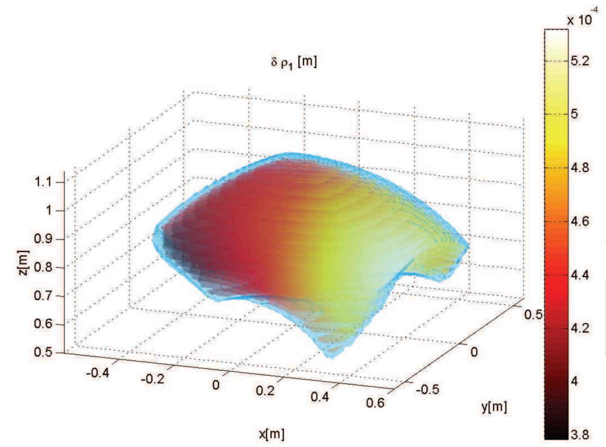


Fig 9: $\delta\rho_1$ for $\varphi = 0, \theta = 0°$

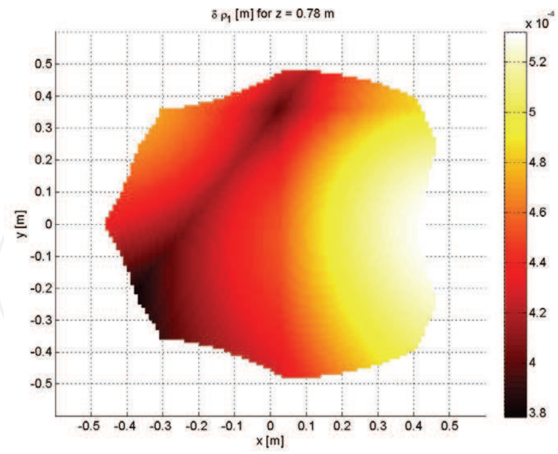


Fig 10: $\delta\rho_1$ for $z = 0.78m, \varphi = 0, \theta = 0°$

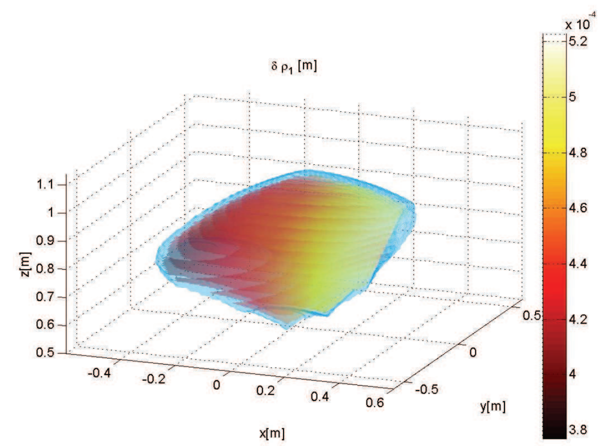


Fig 11: $\delta\rho_1$ for $\varphi = 0, \theta = 20°$

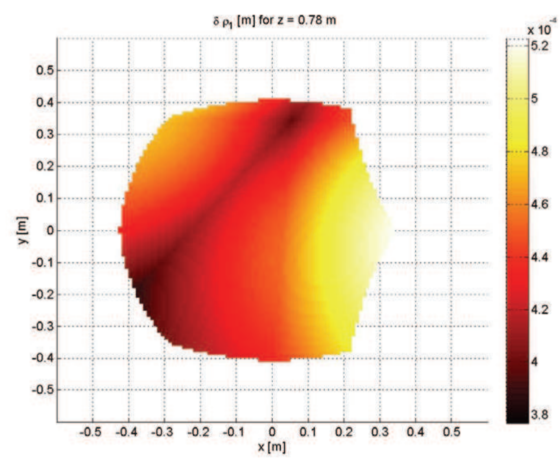


Fig 12: $\delta\rho_1$ for $z = 0.78m, \varphi = 0, \theta = 20°$

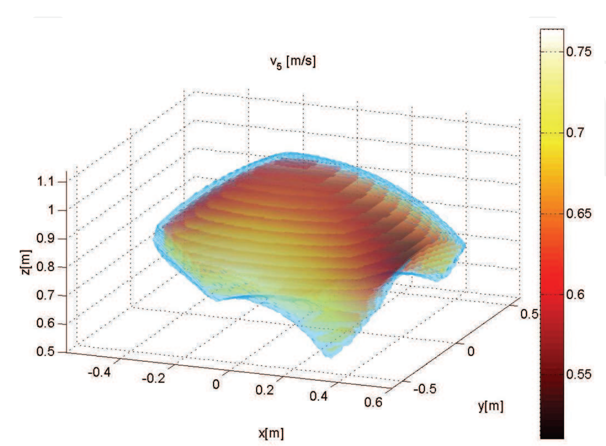


Fig 13: v_5 for $\varphi = 0, \theta = 0°$

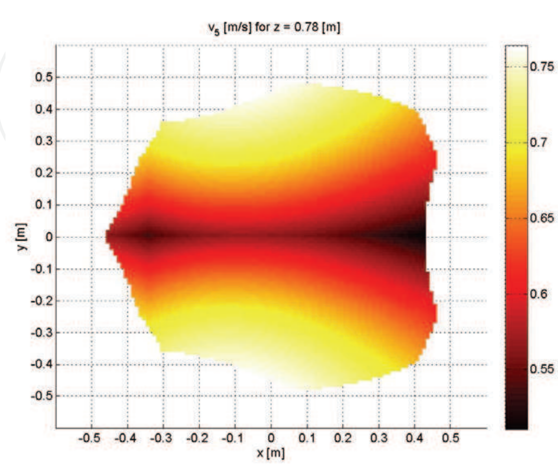


Fig 14: v_5 for $z = 0.78m, \varphi = 0, \theta = 0°$

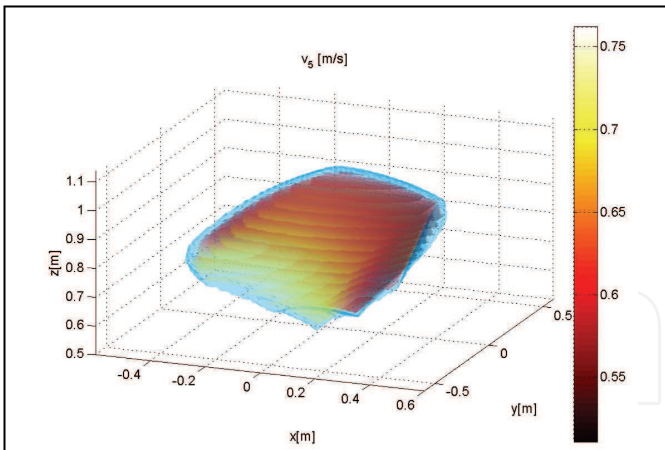


Fig 15: v_5 for $\varphi = 0, \theta = 20°$

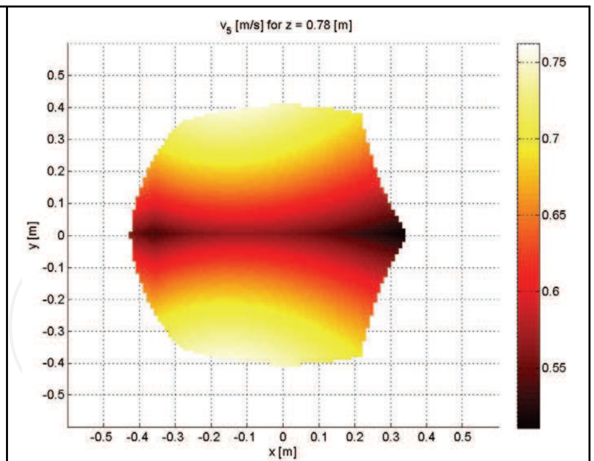


Fig 16: v_5 for $z = 0.78m, \varphi = 0, \theta = 20°$

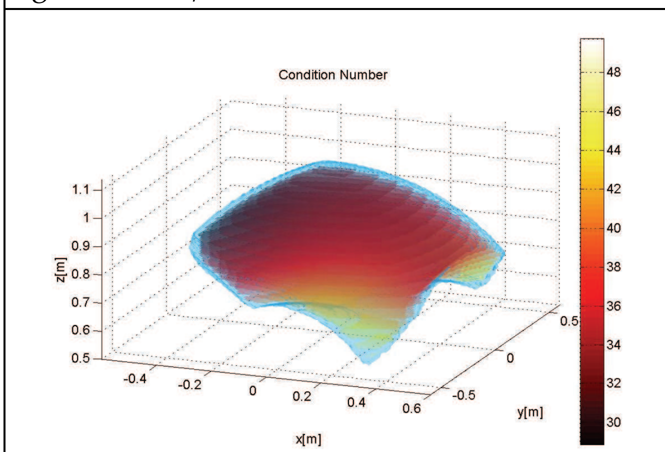


Fig 17: The condition number distribution for $\varphi = 0, \theta = 0°$

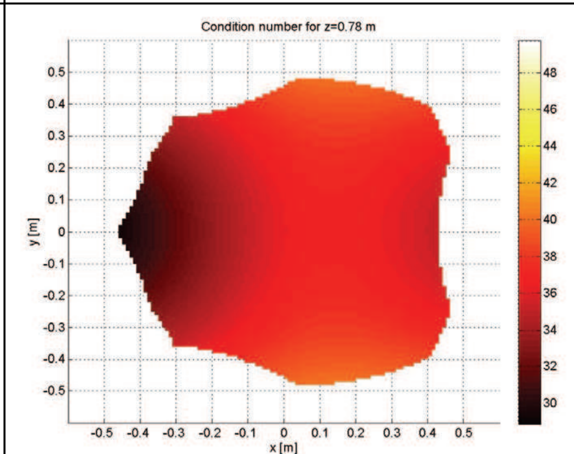


Fig 18: The condition number distribution for $z = 0.78m, \varphi = 0, \theta = 0°$

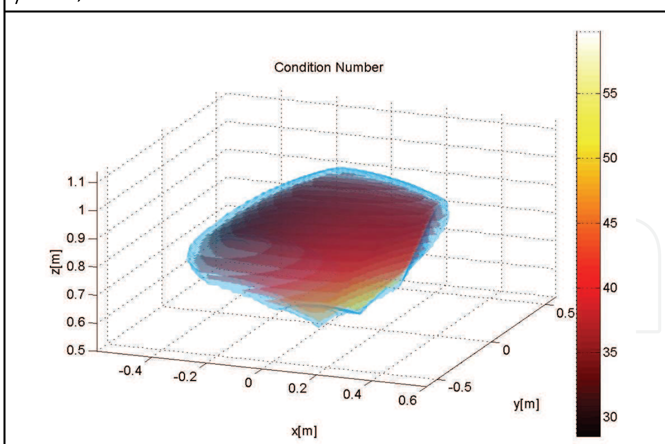


Fig 19: The condition number distribution for $\varphi = 0, \theta = 20°$

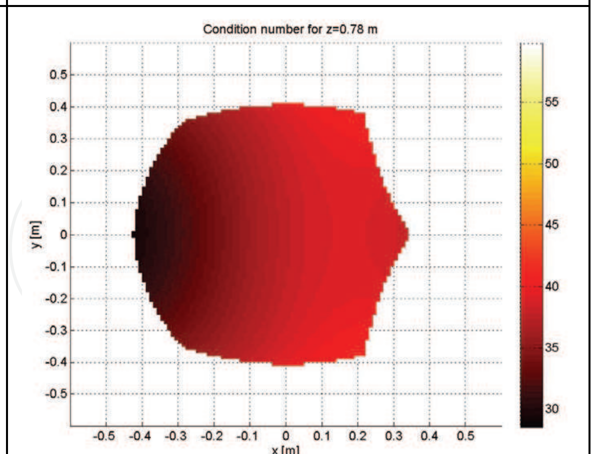


Fig 20: The condition number distribution for $z = 0.78m, \varphi = 0, \theta = 20°$

5. Conclusion

In this chapter, we investigated the optimal design problem of a parallel manipulator with five degrees of freedom that will be used in a high-speed stitching unit as a guidance mechanism for a novel sewing head. First, we reviewed the kinematics of the manipulator. Starting from the requirements list, we derived performance indices that allowed us to evaluate the adequacy of the manipulator for this application. Finally, we developed a numerical procedure that provides many design solutions, which satisfy all requirements. Owing to the iterations that may occur during the design process, the designer may consider different solutions. This allows one to take into account other requirements, such as manufacturing capabilities, available actuators on the market, costs etc … The presented robot stitching unit can be used to assemble reinforcement textiles for the aerospace, automotive, rail vehicles and shipbuilding industry.

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