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On the Optimal Design of Cable Driven Parallel Robot with a Prescribed Workspace for Upper Limb Rehabilitation Tasks

Laribi Med Amine[1*], Carbone Giuseppe[2,3], Zeghloul Saïd[1]

1. *Department of GMSC*, *Pprime Institute*, *CNRS - University of Poitiers - ENSMA - UPR* 3346, *Poitiers*, *France*
2. *Department of Mechanical*, *Energy and Management Engineering*, *University of Calabria*, 87036 *Rende*, *Italy*
3. *CESTER*, *Technical University of Cluj-Napoca*, *Muncii Ave*. 103-105, 400641 *Cluj-Napoca*, *Romania*

Abstract

This paper deals with an optimization approach to design a cable driven parallel robot intended for upper limb rehabilitation tasks. The cable driven parallel robots have characteristics that make them best candidate for rehabilitation exercise purposes such as large workspace, re-configurable architecture, portability and cost effectiveness. Here, both the cable tensions that are needed to move a wristband as well as the workspace need to be carefully optimized for fulfilling the prescribed operation tasks. A specific case of study is addressed in this work by referring to LARM wire driven exercising device (LAWEX), which is applied to upper limbs exercises. To that end, a motion capture system is used to collect quantitative data on the prescribed workspace of a human upper limb. A specific optimization problem is settled up for considering combining two optimization goals, namely, the smallest robot size reaching a prescribed workspace and the minimum cable tension distributions. A sequence of optimization steps is defined using Genetic Algorithms (GAs) applied to LAWEX robot. The proposed objective function is based on a mathematical formulation of the power of a point with respect to bounding surfaces in combination with a performance index to show the distributions of the minimum cable tensions.

Keywords: LAWEX robot design, bionic robot, cable-driven robots, optimization, power of the point, rehabilitation tasks

1 Introduction

The rehabilitation of the upper or lower limb after neurological injury, illness or disease is often slow and difficult. In this scope, the therapists have to achieve as much function as possible and work towards an individual's own goals. This clinic action is expensive and time request. In that regard, the robotic researchers focus on the development of new and innovative technologies based on the use of powerful mechatronic systems for rehabilitation, such as the development of cable driven robot[1–3]. The systems enable patients reach their goals in a fast, more responsive and motivating way. This helps doctors and therapists guide their patients through the rehabilitation process in faster, goal focused and cost effective way.

Cable driven parallel robots present many advantages among classic robots, namely parallel and serial robots[4]. The intrinsic flexibility of cables is one of the major characteristic of cable driven parallel robots, which leads them to provide excellent performances as the light weight, high velocity and acceleration[5,6]. In addition, the ease of assembly and reconfiguration make them well suited for rehabilitation devices[7]. In literature, we can list some examples of cable driven robots for rehabilitation. For instance: MARIONET and STRING-MAN are dedicated to gait rehabilitation proposed by Merlet[8] and Surdilovic *et al*.[9], respectively. NeReBot, CALOWI and MACARM are devices dedicated to upper limb rehabilitation proposed by Rosati *et al*.[10], Ceccarelli[11] and Mayhew *et al*.[12], respectively.

The design approaches are linked in most of the time to specification requirements defined for instance by a prescribed workspace[13–15], stiffness properties[16] and/or kinematic behaviour including pose accuracy, maximum operation speed and maximum output force[17]. As well and due to the system complexity, these approaches are solved based on optimisation processes under mono or multi criteria design. Parallel robots have been addressed with optimal design approaches with multi-criteria formulation in many works[18–20]. On other side, cable driven parallel robots (considered close to

***Corresponding author:** Med Amine Laribi
E-mail: med.amine.laribi@univ-poitiers.fr

parallel robots family) are less studied in a multi-criteria optimal approach[21].

The present work puts forward an approach dedicated to design a cable driven parallel robot. Multi-criteria optimal approach is proposed as based on the distance computation and the cable tension values. The first criterion allows locating a point, defined by its coordinates, compared to the cable driven parallel robot workspace using the power function definition of a point. The second criterion is based on the minimum cable tension at any position within the workspace.

The paper is structured as follows: Section **2** introduces the cable driven parallel robot as well as its kinematics description and wrench set. The specification requirements, to be satisfied by the cable driven robot, are defined by a prescribed workspace carried out through the record of rehabilitation exercises of the upper limb. Section **3** formulates the multi-criteria optimization problem leading to the optimal design variables for the LARM wire driven exercising device (LAWEX) robot sweeping a prescribed workspace and a minimal distribution of cable tensions. The implementation of the optimization algorithm and the numerical results of the cable driven parallel robot for upper limb rehabilitation are presented. Section **4** summarises some remarking outcomes and perspectives of the present study.

2 Characteristics and design requirements

2.1 System description: LAWEX robot

The main difference between analysis of a cable-driven parallel robot and other parallel architecture robots is related with the cables being only able of pulling. This characteristic leads to a mandatory condition, which should be verified by each cable, and only a positive tension can be accepted. Consequently, the workspace of cable driven robot is defined by all poses in Cartesian space of the end-effector where all cables tensions are positive. Many researches addressed the problems related with the identification problem of the feasible workspace kinds due to the cable behaviour.

In particular, constraints for LAWEX robot are itemized here:

(1) Each motor is connected to one cable; and therefore in the considered LAWEX robot, there are 3 motors and 3 cables.

(2) Each cable of the robot should present a positive tension at all times; this is due to the only-pull property.

(3) Only end-effector positions, which are leading to static equilibrium, are considered.

(4) The end-effector is defined by a point mass, only position is considered and not orientation. Thus, forces may be exerted but not moments.

(5) Dynamic effects are neglected as referring to the slow speeds of limb exercising.

A particular attention is given in this work to workspace of cable driven parallel robot. LAWEX robot dedicated to rehabilitation tasks is considered as a case of study. The first prototype of LAWEX robot, Fig. 1, has been developed in Cassino[4,13]. This cable robot design is inspired to facilitate the interaction with patient during the rehabilitation exercises[9], which explains its parallelepiped corner architecture. The patient arm is related to the end-effector of LAWEX robot *via* a wristband to be moved in translation through cables in pull and in equilibrium with gravity[10]. One notices that the considered LAWEX robot configuration includes three actuators (MX-64 dynamixel with torque equal to 6 Nm) and three cables.

Three cables are used to move the end-effector and each one controlled by an actuator. The gravity, as shown in Fig. 2, contributes to maintain the only-pully condition.

The architecture of the cable driven parallel robot is depicted in Fig. 2. The three cables as well as three actuators are located in the upper plane at a d distance from the ground. The location of each actuator $M_{i,\{i=1,2,3\}}$ is given by the cartisian coordinates of point $C_{i,\{i=1,2,3\}}$ in the frame (O, x, y, z). The position vector of each point can be written as:

$$\boldsymbol{OC}_1 = [a \quad r\sin\theta \quad d]^{\mathrm{T}}, \tag{1}$$

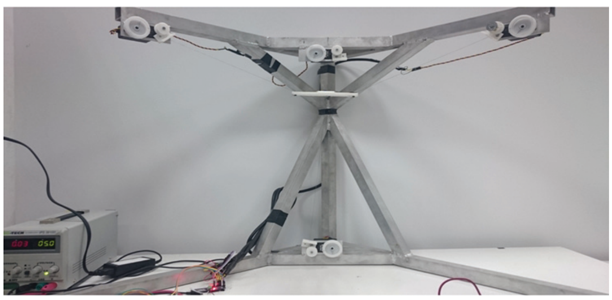

Fig. 1 A prototype of LAWEX robot at LARM.

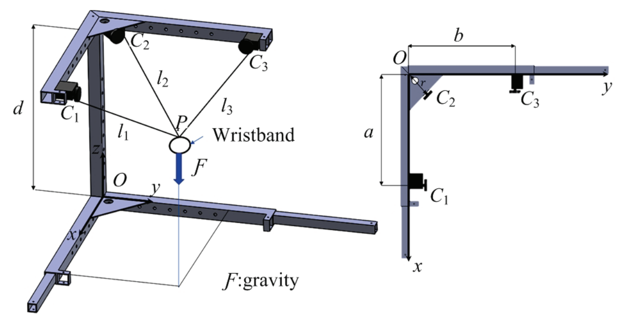

Fig. 2 The cable-driven parallel robot and a wristband as its end-effector.

$$\boldsymbol{OC}_2 = [r\cos\theta \quad r\sin\theta \quad d]^{\mathrm{T}}, \tag{2}$$

$$\boldsymbol{OC}_3 = [r\cos\theta \quad b \quad d]^{\mathrm{T}}, \tag{3}$$

with, $\theta = \pi/2$.

According to these vectors, the LAWEX robot can be described by four independent design variables r, a, b and d. These design variables will appear in the expression of cable lengths, l_i, which is bounded between $l_i^{\min}$ and $l_i^{\max}$.

The Inverse Kinematic Model (IKM) addresses the problem of determining the lengths at rest of the cables for a given pose of the platform. IKM requires solving a square system of equations where each one can geometrically describe a sphere centred on point C_i with radius l_i. For a given point on the platform, point P on the wristband (Fig. 2) defined by its coordinates, the relation between design variables and the cable length is written as, for $i = 1, 2, 3$:

$$(X_p - x_{C_i})^2 + (Y_p - y_{C_i})^2 + (Z_p - z_{C_i})^2 = l_i^2. \tag{4}$$

The workspace that is accessible by the point P is a volume in Cartesian space. This volume is the intersection of three simple geometric forms, three spheres, expressed mathematically by the Eq. (1). If a bounding condition is considered, the following square system of equations can be written:

$$(X_p - x_{C_i})^2 + (Y_p - y_{C_i})^2 + (Z_p - z_{C_i})^2 = l_{\max}^2, \tag{5}$$

$$(X_p - x_{C_i})^2 + (Y_p - y_{C_i})^2 + (Z_p - z_{C_i})^2 = l_{\min}^2. \tag{6}$$

Eqs. (5) and (6) are useful to locate a given point in space defined by its coordinates. The point location is achieved and compared to the accessible workspace as based on the mathematical definition of the power of the point[22]. If one considers a point with coordinates X, Y, and Z and a given LAWEX robot, the point is inside the accessible workspace if and only if the following two equations are satisfied:

$$\mu_{\max}^i(P) = (X - x_{C_i})^2 + (Y - y_{C_i})^2 + (Z - z_{C_i})^2 - l_{\max}^2 \le 0, \tag{7}$$

$$\mu_{\min}^i(P) = (X - x_{C_i})^2 + (Y - y_{C_i})^2 + (Z - z_{C_i})^2 - l_{\min}^2 \ge 0. \tag{8}$$

A boundary of the accessible workspace is depicted in Fig. 3. This geometric construction is obtained using Eqs. (4) and (5) and for $z_{C_i} = d$. It is important to mention that the obtained workspace represents all positions reachable for the platform but not necessary for satisfying the condition of only-pulling on cables. This issue will be considered in section **2.3**.

2.2 Prescribed workspace: rehabilitation task

In this section, the rehabilitation exercise was studied in order to identify the prescribed workspace to be considered in the design procedure of the cable driven parallel robot. This step is carried out with the assistance of experts in physiotherapy and neurology. The rehabilitation task is focused on the upper limb motion and specifically on the motion of the shoulder joint with an unfolded arm. To that end, a patient has been asked to perform a motion that we recorded using the Vicon motion capture system (Fig. 4). A set of high-resolution cameras allowing detecting a number of reflective markers has been used. The cameras of Vicon system are connected to acquisition platform unit defined by a host PC with Nexus software for processing.

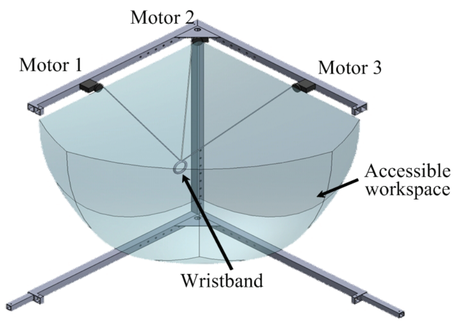

Fig. 3 A 3D representation of accessible workspace of a cable driven robot.

The Nexus software allows to visualize in a 3D environment the detected markers and, specifically, to calculate positions of the used 19 markers. More details on additional experimentations and rehabilitation exercise can be found in Refs. [13] and [21]. After the post-processing step, a real trajectory of a rehabilitation task is obtained. Here, the reconstruction models under Nexus are composed of three segments (arm, forearm and torso) as shown in Fig. 5.

The point P is located on the center of rotation of the wrist and its coordinates are computed as a middle point between markers RAD and ULNA, as shown in Fig. 5. A trajectory can be obtained using successive positions of point P after experimental motion tracking, corresponding to the rehabilitation exercise. All matrix computations from segment reference frame to the fixed terrestrial reference frame are implemented under Matlab[24]. In addition to the trajectory performed to move the joint without any assistance to the muscles surrounding the joint, the range of motion characterising the patient exercise is reported in Table 1. In order to facilitate the comprehension, the range of motion is represented on a sphere and slices on this sphere along frontal, transverse and sagittal planes are given in Fig. 6.

The obtained range of motion is referring to a healthy subject. This choice is motivated by the fact that the prescribed workspace should reflect a larger range of motion as possible but based on a real case. This workspace/trajectory defined by a set of position in space will be considered as an input for the optimal design of the cable driven parallel robot.

Fig. 4 Motion capture system set-up and subject with markers.

Table 1 Angle limits in frontal, transverse and sagittal planes

		Min (°)	Max (°)
Extended forearm	Frontal	−124	53
	Transversal	−30	98
	Sagittal	−87.5	140

2.3 Wrench set analysis

The positive tensions condition should be satisfied at all poses of the mobile platform of a cable driven parallel robot. The identification of the accessible workspace is not enough to perform the design issue. For the case of LAWEX robot, the maximum achievable workspace is a trigonal prism. The three motors constitute the three upper vertices of this trigonal prism, as shown in Fig. 7. The prescribed workspace must be inside this static equilibrium workspace. Additional conditions will be discussed in this paragraph through the wrench set analysis.

The cable driven robot accomplishes a motion during the desired tasks by exerting wrenches on the end-effector. For a given pose, it is possible to compute the set of all possible wrenches that the cables can apply to the end-effector.

Considering positive tension in all cables, the Jacobian relationship for parallel robots can be applied for cable driven robots. Thus, the cable wrench set can be computed by examining the positive range space of the transpose of the Jacobian matrix. The linear relationship between the cable tensions, $\boldsymbol{T}$, and the resulting wrench, $\boldsymbol{\$}$, applied on the end-effector can be described using:

$$\boldsymbol{\$} = \boldsymbol{J}^{\mathrm{T}}\boldsymbol{T}, \quad \text{with} \quad t_{i\in\{1,2,3\}}^{\max} \geq t \geq t_{i\in\{1,2,3\}}^{\min} \tag{9}$$

where $\boldsymbol{T}$ is cable tensions vector given by:

$$\boldsymbol{T} = [t_1, t_2, t_3]^{\mathrm{T}}. \tag{10}$$

$\boldsymbol{J}^{\mathrm{T}}$ is the transpose of Jacobian matrix:

$$\boldsymbol{J}^{\mathrm{T}} = [\$_1, \$_2, \$_3], \tag{11}$$

with $\boldsymbol{\$}_i$ being the wrench along the ith cable defined by the unit vector $\boldsymbol{u}_i$ along calble i and vector $\boldsymbol{c}_i$ from P (center of the mass of the end-effector), as shown in Fig. 8.

$$\boldsymbol{\$}_i = \begin{Bmatrix} \boldsymbol{u}_i \\ \boldsymbol{c}_i \times \boldsymbol{u}_i \end{Bmatrix} = \begin{Bmatrix} \boldsymbol{PC}_i \\ 0 \end{Bmatrix}. \tag{12}$$

The constant external wrench is applied to the end-effector. Typically, the gravitational wrench, $\boldsymbol{\$}_g = \begin{Bmatrix} m\boldsymbol{g} \\ 0 \end{Bmatrix}$, where m is the mass of the end-effector (about 1.5 kg in the case of the forearm with the wristband) and $\boldsymbol{g}$ is the gravitational vector, directed downward.

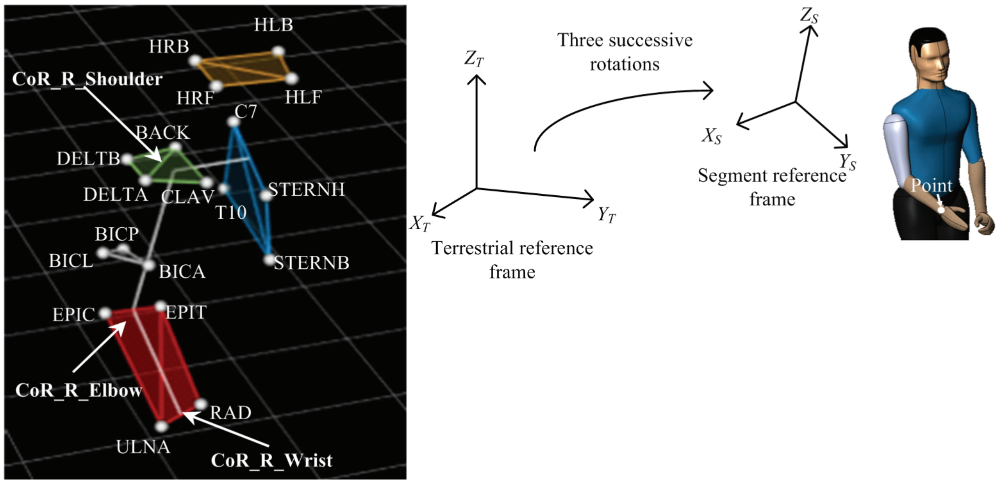

Fig. 5 Reconstruction of several detected markers into segments: arm, forearm and torso.

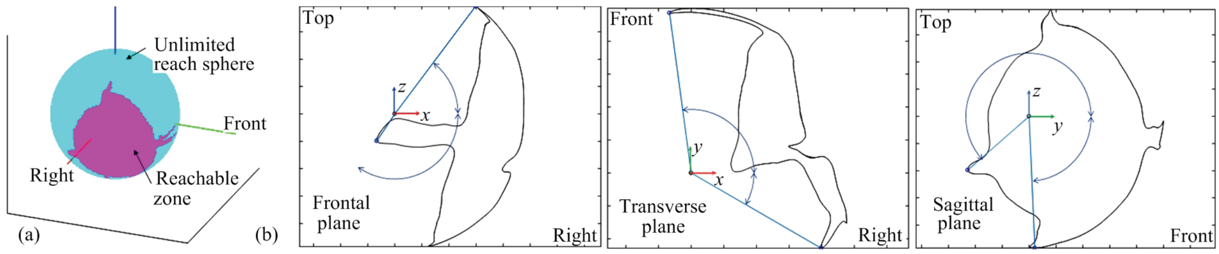

Fig. 6 (a) Shoulder range of motion for extended arm; (b) RoM projection on frontal, transverse and sagittal planes.

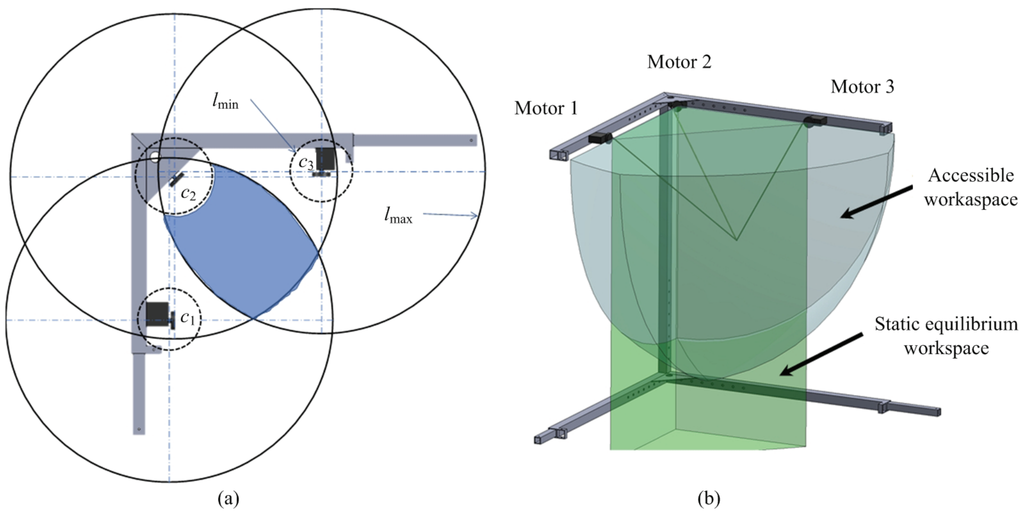

Fig. 7 (a) Slice of the accessible workspace in *XY* plane at $Z = d$; (b) Static equilibrium workspace for a three-cable.

Dexterity index is widely used for determining the workspace performance of a cable-driven robot and as a cost function in design optimization[24,25]. This index is defined by Gosselin as the condition number of the Jacobian matrix[17]. The dexterity index indicates how close the end-effector pose is to singularity and informs about the system performance in terms of velocity and force transmission. In this paper, the dexterity index is considered and its distribution is computed in section **4**.

3 Cable robot design and optimization process

3.1 Formulation of the problem

The aim of this section is to formulate the optimization problem of selecting the independent design variables for the LAWEX robot having the prescribed trajectory within its workspace with minimum positive tensions in the cables. For the design of the driven cable parallel robot, two constraints should be satisfied: a non-negative cable tension and a non-negative power function for each point on the prescribed workspace/trajectory. All feasible solutions that will be found by the proposed design approach should verify the two previous conditions. The solution that minimizes the maximum tensions over all the cables will be selected and considered as an optimal one.

The prescribed trajectory, noted by **Ω**, is given by a set of points in 3D space. This trajectory is linked to the prescribed workspace arising from the real motion of rehabilitation defined at section **2.2**.

The proposed approach is summarized in Fig. 9 and the corresponding general optimization problem can be formulated as follows:

Given: Prescribed trajectory, set of points in 3D space derived from rehabilitation movements.

Find: Optimal independent design variables of the LAWEX robot having the smallest workspace that:

(1) Includes prescribed trajectory.

(2) Minimizes the maximum tensions over all the cables.

The general associated optimization problem, with n parameters for a suitably chosen objective function $F(\boldsymbol{I})$ can be stated as:

$$\min F(\boldsymbol{I}) \tag{13}$$

Subject to

$$\mu^{i}_{\min}(\boldsymbol{I}) \geq 0 \quad \text{for} \quad i = 1, 2, 3,$$

$$\mu^{i}_{\max}(\boldsymbol{I}) \leq 0 \quad \text{for} \quad i = 1, 2, 3,$$

$$t_i^{\min} \leq t_i(\boldsymbol{I}, P) \leq t_i^{\max} \ \text{for } i = 1, 2, 3 \text{ and } \boldsymbol{\$} = \boldsymbol{J}^{\mathrm{T}}\boldsymbol{T}.$$

For every trajectory to be generated by LAWEX robot, cable-based parallel robot for rehabilitation, the vector of independent design variables is defined as:

$$\boldsymbol{I} = [a \ \ b \ \ r \ \ d \ \ S_x \ \ S_y \ \ S_z]^{\mathrm{T}}. \tag{14}$$

The last three elements of the design vector, Eq. (13), represent the Cartesian coordinates of the center of the shoulder. The optimal location of this joint will be investigated by the proposed algorithm, which will handle the optimal placement problem of the cable robot compared to the patient. Fig. 10 shows the way how the shoulder joint, point O_s, is located in (x, y) plane, respectively by S_x and S_y.

3.2 Optimisation process

One of kinematic properties of serial and parallel robots is their workspaces. All accessible poses by the end-effector allow building the workspace, which can be described in most of the cases by an association of simple geometric forms[26,27]. A mathematical formulation of the workspace can then be written and integrated in the expression of an objective function[28,29]. An additional kinematic property, as singularities distribution, can be associated and handled by the objective function. In the present formulation, we address the design problem of a cable-driven parallel robot for prescribed workspace with minimum tension over all the cables.

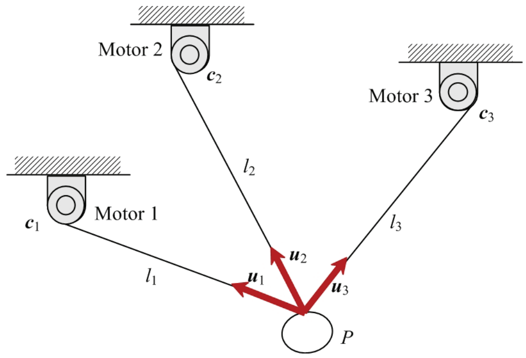

Fig. 8 Diagram of kinematic parameters.

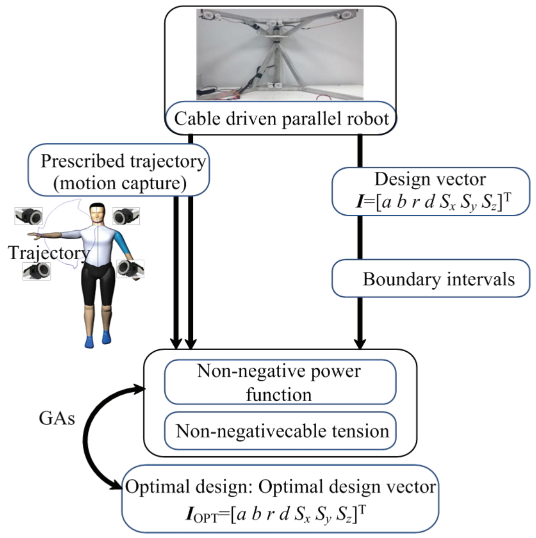

Fig. 9 Optimal design approach of cable driven parallel robot for prescribed workspace.

Due to the fact that a cable can only exert a pulling force, workspace analysis of LAWEX robot is mainly limited by the constraint of keeping non-negative tensions in all the cables at all times. The constraint of having non-negative tensions for all reached poses, defines the so-called Wrench-Feasible Workspace (WFW). For the design of LAWEX robot, this condition has to be satisfied for each pose of a given prescribed workspace.

The objective function to minimize $F(\boldsymbol{I})$, Eq. (11), handles the both constraints linked to the desired workspace and the cable tensions. The first part F_1 of the objective function given by Eq. (12), is defined by functions $|\mu^i_{\min}(\boldsymbol{I},P)|$ and $|\mu^i_{\max}(\boldsymbol{I},P)|$ and compute distances between the point P and the bounding surfaces of the robot workspace. The expressions $\mu^i_{\min}$ as well as $\mu^i_{\max}$ applied to a point P allow to compute distances to the surfaces defined by $\mu^i_{\min}=0$ as well as $\mu^i_{\max}=0$.

A performance index is proposed, for the second part F_2 given by Eq. (13), to show the distribution of the minimum cable tensions in a specified region of the workspace. This index is a normalized quadratic sum of the force tensions and computed subject to a positive cable tension condition.

The optimal design vector of the LAWEX robot, $\boldsymbol{I}_{\rm opt}=[a\ b\ r\ d\ S_x\ S_y\ S_z]^{\rm T}$, with a prescribed trajectory $\boldsymbol{\Omega}$ inside its workspace, will be obtained through the optimisation process as a final result.

Numerous optimization techniques can be used to find the optimal solution to the problem specified in Eq. (9). The procedure consists of finding the combination of design variable values that yields to the best objective function value, while satisfying all the equality and inequality constraints.

Some techniques such as flooding techniques, simulated annealing can have much better chance of finding the global or near global optimum than the other algorithms. They still cannot guarantee the convergence. Genetic algorithms (GAs) differ from traditional search and optimization methods[30]. GAs proceed in parallel from a population of points. This solver has the ability to avoid being trapped in local optimal solution. The fitness score, obtained from objective functions, is directly used without other derivative or auxiliary information. Due to all previous significant points and the successful use in design issue[31], the GAs are applied here.

A penalty function method is used to handle the constraints and to ensure that the fitness of any feasible solution is better than the infeasible ones. The objective function is accordingly constructed as:

$$F(\boldsymbol{I})=F_1(\boldsymbol{I})+F_2(\boldsymbol{I})+F_{31}(\boldsymbol{I})+F_{32}(\boldsymbol{I}), \tag{15}$$

with F_1 is the power function part of the fitness function:

$$F_1(\boldsymbol{I})=\sum_{k=1}^{K}\frac{\sum_{i=1}^{3}|\mu^i_{\min}|+\sum_{i=1}^{3}|\mu^i_{\max}|}{\sqrt{\sum_{i=1}^{3}(\mu^i_{\min})^2+\sum_{i=1}^{3}(\mu^i_{\max})^2}}. \tag{16}$$

F_2 is the normalized quadratic sum of the force tensions and given by:

$$F_2(\boldsymbol{I})=\frac{1}{\max(\boldsymbol{T})}\cdot(\boldsymbol{T}^{\rm T}\cdot\boldsymbol{T}), \tag{17}$$

and F_{31} and F_{32} are penalty functions defined respectively as:

$$F_{31}(\boldsymbol{I})=\sum_{k=1}^{K}(\sum_{i=1}^{3}\delta^i_{\min}(\boldsymbol{I},P)+\sum_{i=1}^{3}\delta^i_{\max}(\boldsymbol{I},P)), \tag{18}$$

where

$$\delta^i_{\min}(\boldsymbol{I},P)=\begin{cases}0 & \mu^i_{\min}(\boldsymbol{I},P)\geq 0\\ \chi & \mu^i_{\min}(\boldsymbol{I},P)<0\end{cases}, \tag{19}$$

$$\delta^i_{\max}(\boldsymbol{I},P)=\begin{cases}0 & \mu^i_{\max}(\boldsymbol{I},P)\leq 0\\ \chi & \mu^i_{\max}(\boldsymbol{I},P)>0\end{cases}, \tag{20}$$

$$F_{32}(\boldsymbol{I})=\sum_{k=1}^{K}(\sum_{i=1}^{3}\xi^i(\boldsymbol{I},P)), \tag{21}$$

where

$$\xi^i(\boldsymbol{I},P)=\begin{cases}0 & t_i(\boldsymbol{I},P)\geq 0\\ \chi & t_i(\boldsymbol{I},P)<0\end{cases}, \tag{22}$$

Here, χ is a large positive number.

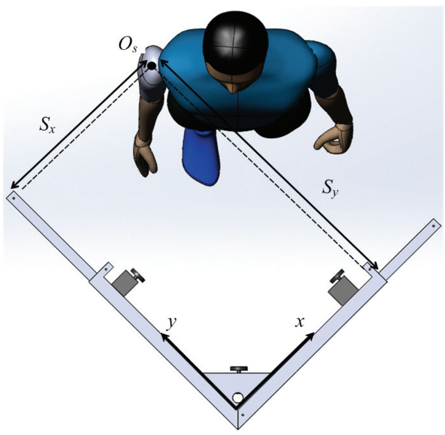

Fig. 10 Center of the shoulder joint, O_s, in (x, y) plane.

$F_{31} = 0$ and $F_{32} = 0$ that the constraints linked to a non-negative power function and non-negative cable tension, respectively, have been satisfied for all points on the prescribed trajectory **Ω**.

3.3 Optimization results

This section presents the obtained results through the implementation of the GAs to solve the optimization problem of the cable driven parallel robot. The outcomes are the optimal design variables of the optimal solution of LAWEX robot allowing reaching all points on the prescribed trajectory. The different steps of GAs are depicted in Fig. 11 and accommodated with the fitness functions Eqs. (11) – (17). The parameters of the Genetic Algorithms are basically the population size equal to 600 and the upper and lower bounds for each design variable useful to initialize the population, given in Table 2.

The approach described in Fig. 11 with its different steps was implemented in MATLAB®, using the Global Optimization Toolbox™ and its genetic algorithm as implemented in the ga() function. As the number of generation in the GAs was limited and due to mutation, different results were generated that finally had to be judged by application. In the following table, the geometry parameters of the most promising optimization result are given. The minimum and maximum limits considered for the tensions are equal to 1 N and 200 N, respectively.

The power of points at a given height $z = d$ is represented in Fig. 12 by a mapping of the objective function F as a function of x and y for a given design vector. The minimum values of F are located at the intersections of the surfaces. The results obtained in this section are the output of the algorithm presented in previous section and developed within Matlab. The optimal solution obtained by the GA is presented in Table 2.

The GAs converge to the optimal solution presented in Table 2 after computation time estimated in about 5 seconds and a number of evaluation function equal to 6000 (100 generations and a population of 600 individuals).

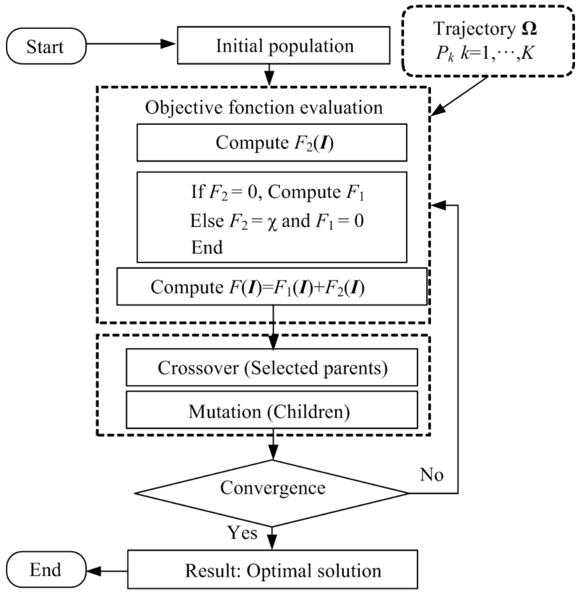

Fig. 11 GAs flow chart to optimal design a cable driven parallel robot.

Table 2 The bounding interval for design variables

$\boldsymbol{I}$	a	b	r	d	S_x	S_y	S_z
max	10	10	10	10	−1500	−1500	−1500
min	1000	1000	500	1500	1500	1500	1500

Table 3 The optimal solution for the cable driven robot, LAWEX

	a	b	r	d	S_x	S_y	S_z
$\boldsymbol{I}_{\text{opt}}$	1086	1086	25	1420	600	600	600

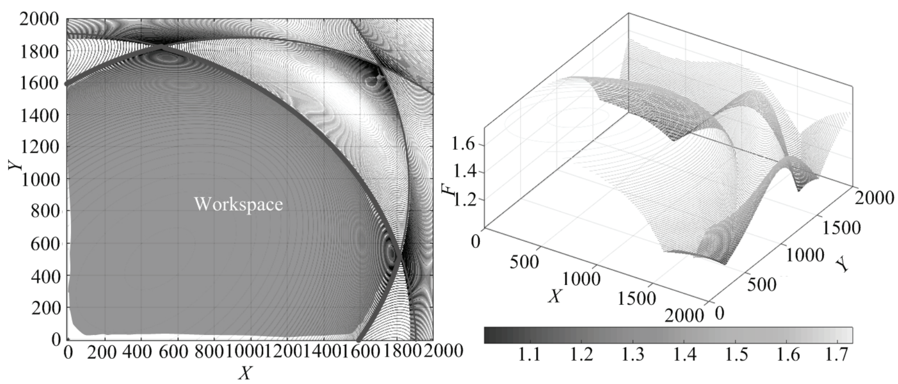

Fig. 12 Power function of the point at a given z function of x and y.

The maximal tension distributions as well as the cable tension index over the static equilibrium workspace are shown in Figs. 13 and 14. The distributions are given for z equal to 1000 and 50, respectively. The optimal solution will avoid singular configurations. The end-effector poses are far from singularity as observed through the dexterity distribution defined as the inverse of the condition number of the Jacobian matrix, Figs. 13 and 14.

The optimal solution is given in Fig. 15 with the prescribed trajectory, **Ω**, obtained through motion tracking detailed in section **2**. The positions of the motors will be adjusted according to the obtained solution, and the cable driven parallel robot can be reconfigurable.

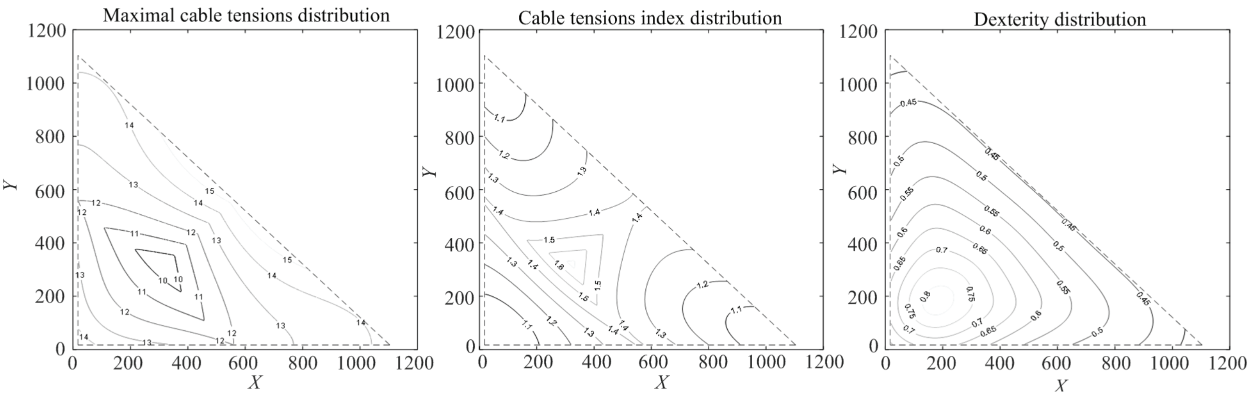

Fig. 13 (a) Distribution of maximal cable tensions in daN; (b) distribution of the cable tensions index; (c) distribution of dexterity index for a given high z = 1000 in (x, y) plane.

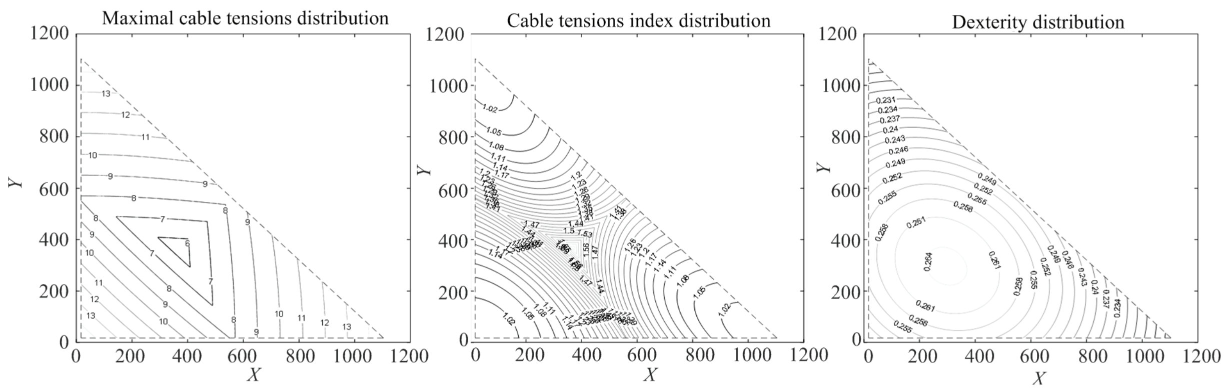

Fig. 14 (a) Distribution of maximal cable tensions in daN; (b) distribution of the cable tensions index; (c) distribution of dexterity index for a given high z = 50 in (x, y) plane.

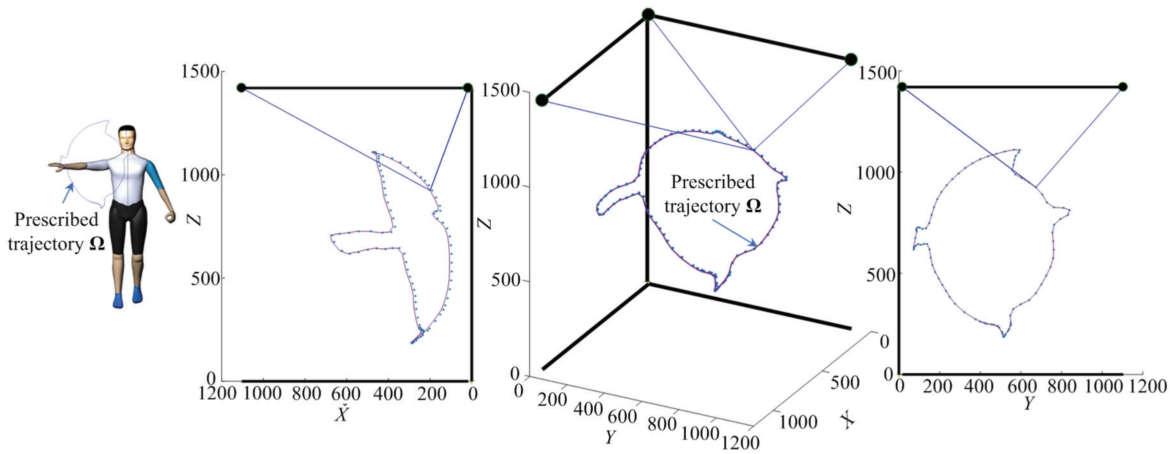

Fig. 15 Optimal solution of cable driven robot with prescribed trajectory **Ω**.

4 Conclusion

In this paper, an optimisation approach has been presented for the design of a cable driven parallel robot with a prescribed workspace. Two optimization goals have been handled by the proposed approach, namely, the smallest robot size reaching a prescribed workspace and the minimum cable tension distributions. The optimisation is carried out using Genetic Algorithms (GAs) subject to the constraints being the non-negative power function and the non-negative cable tensions. The feasibility of the proposed approach is presented through a case of study. Namely, the cable driven LAWEX robot is addressed by referring to its specific application for exercising of human upper limbs. A real subject exercise is obtained through a motion capture session and used as prescribed workspace.

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