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MULTI-OBJECTIVE DESIGN OF SPATIAL CABLE ROBOTS

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ABSTRACT
This paper presents the optimal design of spatial six-cable robots based on single and multi-objective optimization by means of a hybrid genetic algorithm-pattern search approach. The objective functions used are: Global Dexterity Index (GDI), Global Dexterity Uniformity Index (GDUI), Global Stiffness Index (GSI), and Global Stiffness Uniformity Index (GSUI). Firstly, these indices are used separately to obtain the architectural parameters of the robot. Then, mixed performance indices are specified and optimized to obtain the optimal parameters of the robot such as the size of the moving platform, the size of the fixed platform, and the geometric shapes of the two platforms. The obtained results are useful in designing these robots under different conditions.

KEY WORDS
Cable robots, Dexterity, Optimal design, Stiffness, Workspace.

1. Introduction

Cable array robots, also known as cable-suspended robots or cable-driven manipulators, are those robots with cables and winches. The end-effector is connected to the base platform by a number of cables. Cable array robots have several advantages compared to traditional serial or parallel robot. They have high ratio of payload to robot weight and a much larger workspace which is limited mostly by the cable lengths, appropriate for high speed applications [1], lifting heavy loads [2], camera positioning in sports stadiums [3] and many others. Some disadvantages of cable robots are cable interference and inaccuracies at the end-effector as a result of cable stretch.

Based on the number of cables (m) and the number of degrees of freedom (n), there are three categories for the cable robots [4], i.e. the incompletely restrained cable robots ($m<n+1$), the completely restrained cable robots ($m=n+1$) and the redundantly restrained cable robots ($m>n+1$). For the incompletely restrained cable robots, the maximum number of cables is the same as the number of degrees of freedom of the robot. The incompletely restrained six cable robot is the main focus of this paper.

There is some work on the optimal design of classic parallel manipulators. The isotropic configuration of stewart platform robot has been studied by a symbolic method [5]. The dexterity and stiffness of a parallel manipulator have been optimized by Gao *et al.* using genetic algorithms and artificial neural networks [6]. There is a difference between the isotropic design of cable robots and classical parallel robots. For cable robots, the designers must take into account the existence of tension in each cable, in addition to isotropic conditions for classical parallel robots. There are researches dealing with the optimum design of spatial cable robots. Most of the researches only focused on the workspace optimization of spatial cable array robots without considering the dexterity and stiffness indices [7, 8]. In these optimization works, one single objective function (workspace volume index) has been applied in the optimization process. Also, the optimal configuration of a 6-6 cable suspended robot has been obtained separately using the global dexterity index and workspace volume index as its objective functions [9]. In all of the mentioned optimizations, the search spaces of the design parameters have been sliced and then for every set of sliced parameters, the required objective function has been evaluated to obtain the optimal solution. This approach is quite time-consuming and the accuracy of the results depends on the size of the slices. To the best knowledge of authors, there is no complete work done on the optimization of spatial six-cable robots by means of a hybrid genetic algorithm-pattern search approach considering mixed performance indices based on the combination of global dexterity index, global dexterity uniformity index, global stiffness index, global stiffness uniformity index, and workspace volume index.

The organization of this paper is as follows: Section 2 describes the kinematic and design parameters of the robot. In section 3, different kinds of single-objective functions are introduced for the optimization problem. In section 4, different kinds of multi-objective functions are also introduced for the optimization problem. Section 5 presents the method used in optimization and finally, section 6 deals with the results of single and multi-objective optimization presented and interpreted through tables. The obtained results are valuable in designing these robots under different conditions.

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2. Kinematic Modeling

The applied model has six DOF and six cables. Such cable-array robot has a fixed platform, a moving platform and six cables each connected to a connection point on the moving platform A_i and one of the connection points on the fixed platform B_i, allowing six degrees of freedom as shown in Fig. 1. O_F is considered as the origin of the fixed coordinates XYZ which coincides with the mass center of the base platform (*BP*) and O_M is considered as the origin of the body coordinates xyz which coincides with the mass center of the moving platform (*MP*). r_{base} is the radius distance from O_F to the connection points on the base platform B_i and r_{end} is the radius distance from O_M to the connection points on the moving platform A_i. Figs.2 and 3 show γ angle of BP (γ_{base}) and MP (γ_{end}) respectively. The applied diagram of the model is shown in Fig. 4. This expression can be obtained from Fig. 4:

$$l_i = p + [R]^M a_i - b_i \quad i = 1,2,3,...,6 \tag{1}$$

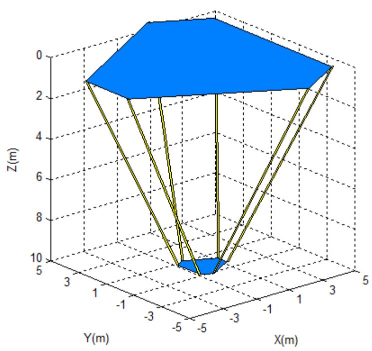

Fig 1. Geometric model

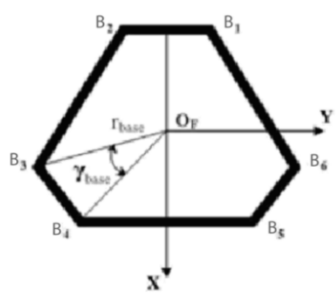

Fig 2. γ_{base} angle for BP

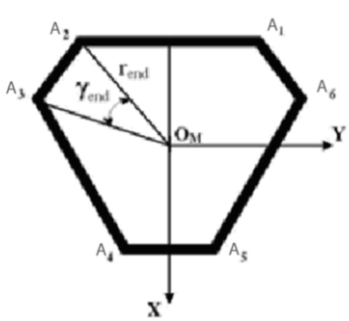

Fig 3. γ_{end} angle for MP

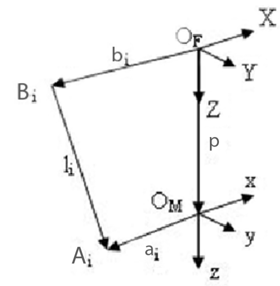

Fig. 4. Vector polygon diagram of the robot

Where b_i is the position vector of the connection points on the base platform B_i, a_i is the position vector of the connection points on the moving platform A_i, p is the position vector of point O_M, l_i is the cable length vector from B_i to A_i and R is the rotation matrix of the *MP* with respect to *BP* with three rotation angles ψ, θ, ϕ respectively about the fixed axes of X, Y and Z and can be defined as:

$$[R] = \begin{bmatrix} \cos\phi\cos\theta & -\sin\phi\cos\psi + \cos\phi\sin\theta\sin\psi & \sin\phi\sin\psi + \cos\phi\sin\theta\cos\psi \\ \sin\phi\cos\theta & \cos\phi\cos\psi + \sin\phi\sin\theta\sin\psi & -\cos\phi\sin\psi + \sin\phi\sin\theta\cos\psi \\ -\sin\theta & \cos\theta\sin\psi & \cos\theta\cos\psi \end{bmatrix} \tag{2}$$

The cable length q_i can be defined as:

$$q_i = |l_i| = (l_i^T l_i)^{1/2} \tag{3}$$

The relation between the cable tensions and external wrench on the MP can be defined as:

$$J^T s = F_{ext} \tag{4}$$

Where s is the vector of cable tensions $s = [s_1 \quad s_2 \quad s_3 \quad s_4 \quad s_5 \quad s_6]^T$ and F_{ext} is the vector of external wrench applied to the end-effector $F_{ext} = [F_X \quad F_Y \quad F_Z \quad M_X \quad M_Y \quad M_Z]^T$ while F_X, F_Y and F_Z are applied forces to the MP and M_X, M_Y and M_Z are applied moments to the *MP*. The transpose of Jacobian matrix is written such that its ith column:

$$J^T{}_i = \begin{bmatrix} \dfrac{l_i}{|l_i|} \\ {}^B a_i \times \dfrac{l_i}{|l_i|} \end{bmatrix}, i = 1,2,...,6 \tag{5}$$

Where:

$${}^B a_i = [R]^M a_i \tag{6}$$

The end-effector is deflected away from its desired position in the presence of the external forces. Increasing the robot stiffness leads to a reduction in deflection of the end-effector. The overall stiffness matrix K_u of the cable array robot can be defined as

$$K_u = J^T diag(k_1, k_2, k_3, k_4, k_5, k_6) J \tag{7}$$

Where

$$k_i = \frac{A_i E_i}{q_i} \quad i = 1, 2, \ldots, 6 \tag{8}$$

In which E_i is the elasticity module of the cables, A_i is the area of the cross section of the cables and q_i is the cable length.

This matrix is always positive semi-definite and symmetric and because of its dependence on the Jacobian, it is also dependent on the posture of the end-effector.

3. Single-Objective functions

Several single-objective functions are introduced for the optimization problem. The Global Dexterity Index (GDI), Global Dexterity Uniformity Index (GDUI), Global Stiffness Index (GSI), Global Stiffness Uniformity Index (GSUI), and Workspace Volume Index (n) are the five objective functions for the optimization problem. We aim at maximizing these five objective functions in the optimization process.

3.1 Dexterity and Dexterity Uniformity Indices

The condition number of the Jacobian matrix is known to be a measure of the control accuracy of the robot [10]. Therefore, it is a very significant index. The minimization of this number keeps the robot away from the singularity configurations. The condition number (k) of the Jacobian matrix J can be written as

$$k(J) = \frac{K_l}{K_s} \tag{9}$$

Where K_l and K_s are the maximum and the minimum singular value of the Jacobian matrix respectively. The condition number takes its values between unity and infinity. The Jacobian matrix J is well-conditioned and far away from singularities, if the condition number of J reaches 1. On the other hand as the condition number approaches infinity the matrix is ill-conditioned. As far as the Jacobian matrix is dimensionally inhomogeneous, there is a problem in computing the condition number. In Eq. (5), the first three columns of the Jacobian matrix J are dimensionless and the last three columns have the units of length. The homogeneous Jacobian matrix J_H is obtained by dividing the last three columns by the characteristic length L [5], i.e., $J_H = JD$ where

$$D = diag(1, 1, 1, \frac{1}{L}, \frac{1}{L}, \frac{1}{L})$$

$$L = \sqrt{\frac{r^2{}_{end}(x^2 + y^2 + 2z^2 + 2r^2{}_{base}\sin^2(60 - \frac{\gamma_{end} + \gamma_{base}}{2}))}{2(x^2 + y^2 + z^2 + \lambda^2)}} \tag{10}$$

$$\lambda = \sqrt{r^2{}_{end} + r^2{}_{base} - 2r_{base}r_{end}\cos(60 - \frac{\gamma_{end} + \gamma_{base}}{2})}$$

The condition number of the homogeneous Jacobian matrix can be computed at each point within the workspace volume of the robot.

The global dexterity index (*GDI*) is a measure of kinematic dexterity of the robot over the entire workspace volume [11]. The global dexterity index (*GDI*) shows how far away the robot is from singularities. High values for *GDI* guarantee good performance with respect to force and velocity transmission [9]. It is based on the distribution of the condition number of the homogeneous Jacobian matrix over the entire workspace volume and is represented by

$$GDI = \frac{\int_V (\frac{1}{k}) dV}{\int_V dV} \tag{11}$$

Where V is the volume of the workspace and k is the condition number of the homogeneous Jacobian matrix. The reciprocal of the condition number ranges in value from zero to one which imposes a bound on *GDI* between zero and one. It is difficult to obtain the exact solution to the integral. Therefore, a discrete version of *GDI* can be defined as

$$GDI \approx \eta_d = \frac{\sum_{i=1}^{n} (\frac{1}{k_i})}{n} \tag{12}$$

Where n is the number of points obtained as the workspace volume of the robot and k is the condition number of the homogeneous Jacobian matrix at a particular point within the workspace volume. This index is not able to show the lower or upper bounds on the dexterity in the workspace. Therefore, another definition called Global Dexterity Uniformity Index is introduced as following

$$\eta_{du} = \frac{\min(\min(\sigma_i))}{\max(\max(\sigma_i))} \tag{13}$$

In which, $\max(\max(\sigma_i))$ and $\min(\min(\sigma_i))$ are the maximum and minimum singular values of the homogeneous Jacobian matrix through the entire workspace, respectively. If the Global Dexterity Uniformity Index

(GDUI) approaches to 1, the dexterity is more uniform and homogeneous through the entire workspace.

3.2 Stiffness and Stiffness Uniformity Indices

Maximizing the stiffness in all directions is more appropriate rather than a particular direction [12]. Therefore, the stiffness index is a suitable measure to use in the design process. It can be computed based on the condition number of the stiffness matrix. The condition number (k) of the stiffness matrix K_u can be expressed as

$$k(K_u) = \frac{E_l}{E_s} \tag{14}$$

Where E_l and E_s are the maximum and the minimum eigen value of the stiffness matrix respectively. The condition number takes its values between unity and infinity. The stiffness matrix is well-conditioned if the condition number reaches 1. On the other hand as the condition number approaches infinity the matrix is ill-conditioned. This quantity can also be computed at each point within the workspace volume of the robot if the the stiffness matrix K_u is homogenized as $K_H = J^T{}_H diag(k_1, k_2, k_3, k_4, k_5, k_6) J_H$ to let the condition number make sense.

The global stiffness index (GSI) can also be defined for all over the workspace volume in the same way as the global dexterity index (GDI).

$$GSI \approx \eta_s = \frac{\sum_{i=1}^{n} (\frac{1}{k_i})}{n} \tag{15}$$

Where n is the number of points obtained as the workspace volume of the robot and k is the condition number of the homogeneous stiffness matrix at a particular point within the workspace volume. This index is not able to show the lower or upper bounds on the stiffness in the workspace. Therefore, another definition called Global Stiffness Uniformity Index is introduced as follows:

$$\eta_{su} = \frac{K_{\min}}{K_{\max}} \tag{16}$$

Where K_{min} and K_{max} are the global minimum and maximum eigen values of the homogeneous stiffness matrix through the entire workspace, respectively [13]. If the Global Stiffness Uniformity Index (GSUI) approaches to 1, the stiffness is more uniform and homogeneous through the entire workspace.

3.3 Workspace Volume Index

Static equilibrium workspace is defined by the number of points where the end-effector can be placed while all the cables must be in positive tension. Therefore, at each point within the search volume if all the elements of the vector of the cable tensions obtained from below Eq. (17) have nonnegative values, that point belongs to static equilibrium workspace volume.

$$\begin{cases} s = J^{-T} F_{ext} \\ under \left| s_i \geq 0 \therefore i = 1, 2, 3, ..., 6 \right. \end{cases} \tag{17}$$

A program was created with the use of Matlab software which tests the points within the search space to define if they belong to the static equilibrium workspace volume of the robot. By setting the values of the parameters of the robot (r_{base}, r_{end}, γ_{base}, γ_{end}, F_x, F_y, F_z, M_x, M_y, M_z), and using Eq. (17), one can obtain the number of points as the workspace volume index (n).

4. Multi-Objective Functions

In this section, multi-objective functions are considered for the optimization of the robot. The multi-objective functions based on the combination of these five global performance indices are considered as follows:

1- Overall dexterity index η_{ODI}

2- Overall stiffness index η_{OSI}

3-Overall mix of dexterity and stiffness indices η_{ODSI}

We aim at maximizing these three objective functions in the optimization process. In the single-objective optimization case, we aim to obtain the best solution. But in the multi-objective optimization, objective functions can conflict with each other, so there is not necessary a best solution. The result of the multi-objective optimization is a set of solutions called Pareto-optimal solutions. By defining the weight parameters of the objective functions, one can determine one of the Pareto solutions for those specified weight parameters.

4.1 Overall Dexterity Index

An overall dexterity index (ODI) of the manipulator can be expressed as follows:

$$ODI = \eta_{ODI} = w_{d_1} \frac{\eta_d}{(\eta_d)_{\max}} + w_{d_2} \frac{\eta_{du}}{(\eta_{du})_{\max}} \tag{18}$$

Where the weight parameters w_{d1} , w_{d2} (w_{d1} , $w_{d2} \in [0\ 1]$ and $w_{d1}+w_{d2}=1$) show the proportion of η_d (GDI),and the proportion of η_{du} (GDUI) in the overall dexterity index, respectively. The variation ranges of η_{du}, η_d are quite different. So $(\eta_d)_{\max}$ and $(\eta_{du})_{\max}$ are used to normalize the functions between zero and one. These two maximum values can be calculated by performing single-objective optimization for each function.

4.2 Overall Stiffness Index

An overall stiffness index (OSI) of the manipulator can be defined as follows:

$$OSI = \eta_{OSI} = w_{s_1} \frac{\eta_s}{(\eta_s)_{\max}} + w_{s_2} \frac{\eta_{su}}{(\eta_{su})_{\max}} \quad (19)$$

Where the weight parameters w_{s1} , w_{s2} (w_{s1} , $w_{s2} \in [0\ 1]$ and $w_{s1}+w_{s2}=1$) show the proportion of η_s (GSI), and the proportion of η_{su} (GSUI) in the overall stiffness index, respectively. The variation ranges of η_{su} , η_s are quite different. So $(\eta_s)_{\max}$ and $(\eta_{su})_{\max}$ are used to normalize the functions between zero and one. These two maximum values can be calculated by performing single-objective optimization for each function.

4.3 Overall Mix of Dexterity and Stiffness Index

An overall mixed performance index which is a weighted sum of overall dexterity index (ODI) and overall stiffness index (OSI) can be formed as:

$$ODSI = \eta_{ODSI} = w_{d_1} \frac{\eta_d}{(\eta_d)_{\max}} + w_{d_2} \frac{\eta_{du}}{(\eta_{du})_{\max}} + w_{s_1} \frac{\eta_s}{(\eta_s)_{\max}} + w_{s_2} \frac{\eta_{su}}{(\eta_{su})_{\max}} \quad (20)$$

Where the weight parameters w_{d1}, w_{d2}, w_{s1}, w_{s2} (w_{d1}, w_{d2}, w_{s1}, $w_{s2} \in [0\ 1]$ and $w_{d1}+w_{d2}+w_{s1}+w_{s2}=1$) show the proportion of η_d (GDI), the proportion of η_{du} (GDUI), the proportion of η_s (GSI) and, the proportion of η_{su} (GSUI) in the overall mix of Dexterity and Stiffness index, respectively. The selection of weight parameters depends on whether the designer wants the manipulation to be closer to which of the properties.

5. Optimization Methodology

An optimization method should be selected to obtain the optimum values of the design parameters. For these functions, it is not possible to solve this problem analytically. Furthermore, derivative–based methods are not appropriate because of the non-smooth behavior of these objective functions. Therefore, intelligent and direct search methods are suitable such as Genetic Algorithm (GA) or Pattern Search (PS) methods or their combination. The random behavior of GA leads to different solutions for various runs. This problem can be solved by using a PS algorithm started from the GA solution so their combination leads to a unique solution. Therefore, a hybrid GA-PS approach will be used in this paper to provide much more accurate results.

5.1 Genetic Algorithm

Genetic Algorithms (GAs) are one of the optimization techniques which work based on the principles of natural evolution. The GAs are appropriate for rapid global search of large and nonlinear spaces [14]. Also, GAs are more useful for the discontinuous problem unlike the conventional gradient-based algorithms.

In the GAs, possible solutions are encoded as chromosomes, which form an initial random population. Then, each member of the population is evaluated by a fitness function. After that a selection operator based on the fitness values is applied to the population. The individuals with higher fitness values have more chance to be chosen and to reproduce offspring with the use of other operators such as crossover and mutation to create the next generation. This process will be repeated for a number of generations till the termination criterion is satisfied. This termination is specified by a predefined maximum number of generations or population convergence condition. The best individual of the last generation is the optimal solution to the problem. The parameters for the Matlab's GA Tool are set as Table 1. The upper bound of γ_{base} and γ_{end} are selected to be 60 degree based on the result of [9]. When both γ_{base} and γ_{end} approach to 60 degree, the workspace volume of the robot becomes zero and therefore the robot is meaningless.

5.2 Pattern Search

Pattern search techniques are a class of direct search methods for optimization. Like the genetic algorithm, PS is often useful for global optimization. It is suitable for non-smooth or discontinuous objective functions. PS algorithm searches a set of points called a mesh, around the current point. The mesh is created by adding the current point to a scalar multiple of a set of vectors called a pattern. If the algorithm finds a point within the mesh that improves the objective function, the new point becomes the current point at the next iteration. The search will terminate after a minimum mesh size is reached., a pattern search function as our hybrid function will start from the final solution obtained by GA. The parameters for the Matlab's PS Tool are set as Table 2.

Table 1
Genetic algorithm parameters

Encoding type	Real
Population size	100
Maximum generation	300
Creation function	uniform
Selection function	stochastic
Mutation function	Adaptive
Crossover function	Scattered
Lower bounds on H=[γ_{base} γ_{end} r_{end}/r_{base}]	[0^o 0^o 0]
Upper bounds on H=[γ_{base} γ_{end} r_{end}/ r_{base}]	[60^o 60^o 2]

Table 2
Pattern search parameters

Poll Method	GPS Positive basis 2N
Complete Poll	on
Search Method	MADS Positive basis 2N
Complete Search	on
Initial Mesh size	1
Expansion Factor	2
Contraction Factor	0.5
Max Iteration	300

6. The Results of Optimization

For obtaining the static equilibrium workspace volume and stiffness of the robot, it is also necessary to make these eight assumptions:

1- r_{base}= 6 m
2- The optimal configuration of the cable robot can be defined as [5].

$$x = y = \theta = \varphi = \psi = 0$$

$$z_{optimal} = r_{base} \sin(60 - \frac{\gamma_{base} + \gamma_{end}}{2})$$

$$r_{end} = r_{base} \cos(60 - \frac{\gamma_{base} + \gamma_{end}}{2})$$

Therefore, $z_{optimal}$ is bounded for any values of γ_{base} and γ_{end} as: $0 \le \frac{z_{optimal}}{r_{base}} \le 0.8660$. Based on this range, the search volume is considered to be two types with these dimensions:
$0 \le Z \le Z_{max}$, $-r_{base} \le Y \le r_{base}$, $-r_{base} \le X \le r_{base}$ Where $\frac{Z_{max}}{r_{base}} = \begin{cases} 1 \\ 2 \end{cases}$

In both of the search volumes, the optimal possible configurations are always inside the two search volumes.
3- The step size along all X, Y and Z axes ($\Delta = \Delta x = \Delta y = \Delta z$) is $\frac{\Delta}{r_{base}} = 0.05$.
4-F_{ext}= $[0\ 0\ 100\ 0\ 0\ 0]^T$ kN
5-E=200 Gpa
6- A=0.0004 m^2
7- The rotation of MP is equal to zero: ψ=0, θ=0 and ϕ=0.
8-All cables have negligible mass and shape a straight line between the connection points on the base platform and the connection points on the moving platform.

A program was created with the use of Matlab software which tests the points within the search space to define if they belong to the static equilibrium workspace volume of the robot. By setting the eight mentioned assumptions, the values of the parameters of the robot, and using Eq. (17), one can obtain this workspace volume of the robot. For those points within the workspace volume, the specified single and multi-objective functions can be evaluated. For the optimization process, a hybrid GA-PS is performed by using Matlab's Genetic Algorithm and Direct Search Tool [15].

6.1 Results Presentation

The results of the three design parameters H= [γ_{base} γ_{end} r_{end}/r_{base}] are presented through Tables (3-6). The weight parameters of the five single-objective functions are considered to be equal for the optimization process. Therefore, based on the number of functions used in a multi-objective function (k), all the weight parameters are equal to ($1/k$). With respect to the results of the Tables (3-6) we can arrive at the following general conclusions:

1- The results of Tables (3-6) show that for all of the objective functions, the γ angle of BP (γ_{base}) is greater than or approximately equal to the γ angle of MP (γ_{end}).
2- The workspace volume index (n) increases by increasing r_{base} and decreases by increasing gamma angle γ_{base}, γ_{end} [7]. Also, for a fixed size of r_{base} and no moments (Mx=My=Mz=0) just like our case (assumptions 1 and 4), the maximum workspace volume index (n_{max}) is independent of r_{end}/r_{base} and occurs at $\gamma_{base}=\gamma_{end}=0$ for both of the search volumes (Z_{max}/r_{base}=1 and Z_{max}/r_{base}=2) [7, 8]. This workspace volume index (n) is also added as an additional objective function ($w_n n/n_{max}$) to the seven objective functions of the Tables 3 and 4 for the optimization problems. In which n_{max} and w_n are respectively the maximum workspace volume index and its weight parameter. Tables 3 and 4 show the optimal parameters of the robot by adding $w_n n/n_{max}$ as an additional objective function ($w_n n/n_{max}$) to the seven objective functions in the case of Z_{max}/r_{base}=1 and Z_{max}/r_{base}=2, respectively. In Tables 3 and 4, the maximum value of all the objective functions nearly occurs at $\gamma_{base}=\gamma_{end}=0$, r_{end}/r_{base}=0.5. Therefore, increasing the range of the robot motion in the Z direction (Z_{max}) has almost no effect on the optimal parameters for these seven objective functions.
3- It is apparent from Tables 3 and 4 that increasing the range of the robot motion (Z_{max}) leads to a small reduction in the values of the three optimal parameters γ_{base} , γ_{end} ,and r_{end}/r_{base} for most of the objective functions.
4- The optimal parameters of the robot are presented through Table 5 and 6 without considering the workspace volume index (n) as an additional objective function in the case of Z_{max}/r_{base}=1 and Z_{max}/r_{base}=2, respectively. It can be observed from Tables 5 and 6 that the values of the optimal parameters obtained by the overall stiffness index η_{OSI} are nearly close to the values of the optimal parameters derived by the

stiffness uniformity index η_{su}. Also, the values of the optimal parameters obtained by the overall dexterity index η_{ODI} are nearly close to the values of the optimal parameters derived by the dexterity uniformity index η_{du} and finally, the values of the optimal parameters obtained by the overall mix of dexterity and stiffness indices η_{ODSI} are nearly close to the values of the optimal parameters derived by the stiffness uniformity index η_{su} .

5- It is clear from Tables 5 and 6 that the values of the three optimal parameters obtained by the stiffness uniformity index η_{su} are greater than their corresponding values in case of using the stiffness index η_s . Also, the values of the three optimal parameters obtained by the dexterity uniformity index η_{du} are also greater than their corresponding values in case of using the dexterity index η_d . In addition, the values of the three optimal parameters obtained by the dexterity index η_d are greater than or equal to their corresponding values in case of using the stiffness index η_s and finally, the values of the three optimal parameters obtained by the dexterity uniformity index η_{du} are greater than their corresponding values in case of using the stiffness uniformity index η_{su} .

6- It can be observed from Tables 5 and 6 that the BP is almost a regular hexagon except in the case of stiffness index η_s and dexterity index η_d . Also, the MP is always an equilateral triangle in case of stiffness index η_s and dexterity index η_d .

7- It is obvious from Tables 5 and 6 that increasing the range of the robot motion (Z_{max}) leads to a reduction in the values of the three optimal parameters γ_{base} , γ_{end} ,and r_{end}/r_{base} for most of the objective functions.

8- By comparing the results of the Tables 3 and 5 both in case of $Z_{max}/r_{base}=1$, one can find that using the workspace volume index (n) as an additional objective function results in a great reduction in the values of the three optimal parameters γ_{base} , γ_{end} ,and r_{end}/r_{base} for all of the objective functions.

9- Based on the results of the Tables 4 and 6, the same principal is also valid in case of $Z_{max}/r_{base}=2$, one can realize that using the workspace volume index (n) as an additional objective function results in a great reduction in the values of the three optimal parameters γ_{base} , γ_{end} ,and r_{end}/r_{base} for all of the objective functions.

Table 3

The optimal parameters of the robot by adding $w_n \frac{n}{n_{\max}}$ as an additional objective function in case of $\frac{Z_{\max}}{r_{base}}=1$

Objective Function	γ_{base}	r_{end}/r_{base}	γ_{end}	Function Value
$\mathrm{Max}(\eta_{su})$	0.8122	0.5062	0.0675	0.5711
$\mathrm{Max}(\eta_s)$	0.8389	0.5067	0.0566	0.9644
$\mathrm{Max}(\eta_d)$	0.8965	0.5069	0.0253	0.9663
$\mathrm{Max}(\eta_{du})$	0.1875	0.5022	0.4107	0.6439
$\mathrm{Max}(\eta_{OSI})$	0.1562	0.5018	0.4278	0.6901
$\mathrm{Max}(\eta_{ODI})$	0.4688	0.5040	0.2578	0.7401
$\mathrm{Max}(\eta_{ODSI})$	0.7591	0.5059	0.1000	0.6584

Table 4

The optimal parameters of the robot by adding $w_n \frac{n}{n_{\max}}$ as an additional objective function in case of $\frac{Z_{\max}}{r_{base}}=2$

Objective Function	γ_{base}	r_{end}/r_{base}	γ_{end}	Function Value
$\mathrm{Max}(\eta_{su})$	0.0395	0.5007	0.2740	0.6503
$\mathrm{Max}(\eta_s)$	0.0001	0.5002	0.0000	0.9994
$\mathrm{Max}(\eta_d)$	0.0000	0.5000	0.0001	0.9999
$\mathrm{Max}(\eta_{du})$	0.0625	0.5014	0.4787	0.7008
$\mathrm{Max}(\eta_{OSI})$	0.0101	0.5000	0.0000	0.7664
$\mathrm{Max}(\eta_{ODI})$	0.1767	0.5018	0.2500	0.8001
$\mathrm{Max}(\eta_{ODSI})$	0.1006	0.5007	0.0000	0.7399

Table 5

The optimal parameters of the robot in case of $\frac{Z_{\max}}{r_{base}}=1$

Objective Function	γ_{base}	r_{end}/r_{base}	γ_{end}	Function Value
$\mathrm{Max}(\eta_{su})$	59.7689	0.8916	23.5912	0.0116
$\mathrm{Max}(\eta_s)$	21.1620	0.6505	0.0002	0.1846
$\mathrm{Max}(\eta_d)$	39.8159	0.7650	0.0001	0.4166
$\mathrm{Max}(\eta_{du})$	59.0312	0.8964	32.5931	0.1692
$\mathrm{Max}(\eta_{OSI})$	59.4609	0.8735	22.8916	0.8502
$\mathrm{Max}(\eta_{ODI})$	59.6464	0.8971	31.9473	0.8663
$\mathrm{Max}(\eta_{ODSI})$	60.0000	0.8852	23.0902	0.8207

Table 6

The optimal parameters of the robot in case of $\frac{Z_{\max}}{r_{base}} = 2$

Objective Function	γ_{base}	r_{end}/r_{base}	γ_{end}	Function Value
$\mathrm{Max}(\eta_{su})$	51.9486	0.8294	10.2303	0.0055
$\mathrm{Max}(\eta_{s})$	0.9432	0.5071	0.0001	0.1652
$\mathrm{Max}(\eta_{d})$	0.9432	0.5071	0.0001	0.3917
$\mathrm{Max}(\eta_{du})$	59.2928	0.8751	20.0165	0.1215
$\mathrm{Max}(\eta_{OSI})$	51.9400	0.8293	10.2300	0.8349
$\mathrm{Max}(\eta_{ODI})$	59.9022	0.8920	19.9193	0.8302
$\mathrm{Max}(\eta_{ODSI})$	59.8745	0.8714	2.9110	0.8017

7. Conclusion

This paper presents the optimal design of a 6-DOF cable robot with respect to multi-objectives based upon the hybrid GA-PS method. Different objective functions such as Global Dexterity Index (GDI), Global Dexterity Uniformity Index (GDUI), Global Stiffness Index (GSI), Global Stiffness Uniformity Index (GSUI), and Workspace Volume Index (n) are considered for the optimization process. Firstly, these indices are used separately to obtain the architectural parameters of the robot. Then, mixed performance indices are specified and optimized to obtain the optimal parameters of the robot such as the size of the moving platform, the size of the fixed platform, and the geometric shapes of the two platforms. The obtained results are valuable in designing these kinds of robots under different conditions. Future work will relate to considering cable length limits and upper tension bounds in the model and optimization process. In the same way, we will include additional objective functions and another optimization method called Multi-Objective Evolution Algorithm (MOEA) to provide a complete set of optimal parameters of the cable robot.

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