# Genetic Algorithm Based Optimization of Cable Attachment Geometry for Maximising Tensionable Workspace in a Planar Cable-Driven Manipulator

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**Abstract.** Cable-driven manipulators are used in applications like rehabilitation devices, assistive exoskeletons, and lightweight manipulators due to low inertia, high force transmission capability, and flexible design architecture. Since cables can only transmit tensile forces, the ability of these systems to generate the desired wrench is limited to the tensionable workspace where all cables remain under positive tension. The size and shape of this workspace depend on the cable attachment points on the robot links. Optimizing these parameters is important for improving the operational capability of cable-driven manipulators. This work presents a Genetic Algorithm (GA) based optimization framework to determine optimal cable attachment parameters that maximise tension feasibility along a predefined joint trajectory. The study considers a planar two-link serial manipulator actuated by four cables. Cable attachment geometry is defined using two parameters the distance from the joint center along the link ($d$) and the offset distance from the link axis ($h$). The proposed optimization method identifies cable attachment parameters that ensure positive cable tensions within specified bounds throughout the trajectory, thereby improving the system's tensionable workspace.

**Keywords:** Cable-driven robots· Tensionable workspace · Cable attachment optimization · Genetic Algorithm.

## 1 Introduction

Cable-driven manipulators (CDMs) are a class of robotic systems in which motion is generated by controlling the length and tension of cables attached to the links [1]. For conventional manipulators, actuators are mounted on joints, but in CDMs, the actuators are mounted on a fixed frame /ground and transmit forces through lightweight cables. This facilitates low-moving inertia and improves the force-to-weight ratio [2]. This structural advantage makes CDMs

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suitable for applications requiring a large workspace and low dynamic mass [3], such as manufacturing systems [4], aerial camera platforms [5], cable-suspended construction robots [6], and rehabilitation devices [7]. However, cables can only transmit tensile forces and cannot push, which introduces unilateral actuation constraints. As a result, the manipulator cannot utilize its entire kinematically reachable workspace unless all cables remain in positive tension [8]. The subset of configurations where feasible positive cable tensions exist is referred to as the tensionable workspace or wrench-closure workspace [9]. A large, well-defined tensionable workspace is important because it ensures that all cables remain in tension and the robot can move smoothly without losing control. This helps the manipulator apply forces properly and operate safely without instability or cable slack [10].

Many researchers have investigated methods to analyze and expand the tensionable or wrench-feasible workspace of cable-driven manipulators so that the robot can reach more positions while keeping all cables in tension. Some studies developed better numerical methods and search algorithms to calculate and expand the feasible workspace by optimizing where cables attach and how they are routed [11]. Other researchers looked at adding more cables or redundancy, which can help maintain positive tension in more configurations and increase the tensionable workspace [9]. Few approaches examined the change in robot geometry by allowing structural parts to reconfigure, which alters the tensionable workspace and makes the system more flexible and stable during motion [12]. Few focused on minimal tension, where cable tensions are controlled in real time to keep the workspace robust against disturbances and improve control over end-effector [13]. Overall, these methods aim to make the tensionable workspace larger, more controllable, and better suited for real tasks.

System parameters, such as motor positions, cable routing, and cable attachment geometry, strongly affect the tensionable workspace of a cable-driven manipulator. Changing the motor's location alters the direction of the cable forces, which can increase or decrease the tensioned workspace in which all cables remain in tension [14]. Similarly, modifying the cable attachment points, such as the distance from the joint ($d$) and the offset ($h$) from the link axis, can change the moment arms of the cable forces, which affects torque generation and workspace [15]. Cable routing strategies, such as co-sharing cables between links, also influence how forces are transmitted through the mechanism and can reshape the tensionable workspace [11]. Therefore, selecting these geometric and design parameters is very important for achieving a larger workspace. In many cases, parameters such as cable attachment points are selected based on trial-and-error [16]. However, the relationship between attachment geometry and tensionable workspace is nonlinear. Small changes in geometry can significantly alter the feasible tension region, and it is mathematically complex to find the optimal configuration using conventional methods [12].

A considerable amount of research has been carried out on the analysis and optimization of cable-driven manipulators. Most of the existing work focuses on analytical models, numerical methods, or geometry-based optimization strategies to improve workspace performance. In short, this study explores a soft-computing approach for determining suitable cable attachment parameters based on a given task trajectory. A Genetic Algorithm (GA) is employed to automatically search for attachment configurations that maintain cable tension feasibility throughout the desired motion. The proposed framework combines null-space-based tension analysis with optimization to systematically evaluate different attachment geometries $(d, h)$ and identify configurations that improve the tensionable workspace. By directly incorporating trajectory requirements into the design process, the method gives a practical alternative to conventional approaches and offers more flexibility in the design of planar cable-driven manipulators.

# 2 Methodology

## 2.1 Modelling

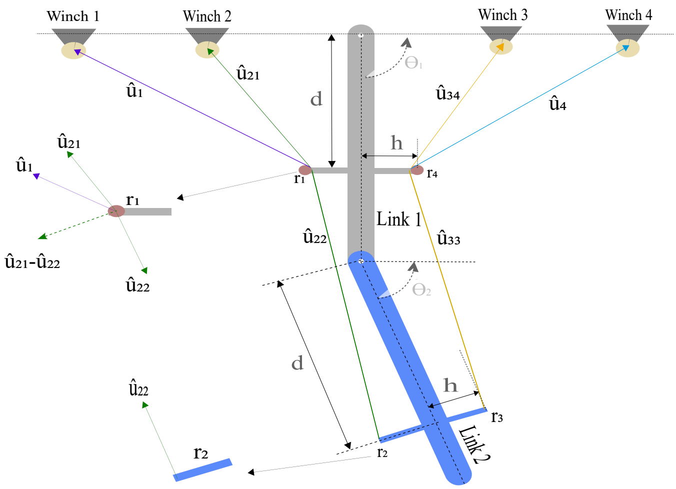



Fig. 1: Schematic of cable driven serial manipulator. $r_j$ is position vector of its cable attachment and $\hat{u_j}$ is unit vector along $j^{\text{th}}$ cable

In this work, a two-DOF planar two-link serial chain manipulator is considered for analysis. Figure 1 shows the schematic of the considered cable-driven serial manipulator that has two rigid links connected to the revolute joints $\theta_1$ and $\theta_2$. As four cables are attached to the link, where $d$ and $h$ represent the cable attachment point and the offset position on the link.

In cable-driven serial chain manipulators (CDSMs), cables can transmit only tensile forces. Therefore, the feasible workspace of the manipulator is restricted to configurations where all cables remain in positive tension. This region is referred to as the tensionable workspace or Wrench Closure Workspace (WCW) [17]. A cable-driven rigid body actuated by 4 cables. To evaluate the tension feasibility of the cable-driven manipulator, the static equilibrium condition of the system is considered. The torque–tension relationship is given by

$$\mathbf{AT} = \boldsymbol{\tau} \tag{1}$$

where $\mathbf{A}$ is the structure matrix, T is the vector of cable tensions, and $\boldsymbol{\tau}$ is the vector of joint torques [9].

The set of poses that a cable-driven system can reach to apply a desired set of torques, such that the tension in each cable remains within a prescribed range $t_{\min}$ and $t_{\max}$, defines the Wrench Feasible Workspace (WFW)[18]. It is a subset of the Wrench Closure Workspace (WCW).

$$\mathbf{A}\boldsymbol{t} = \boldsymbol{\tau}, \qquad t_{\min} < t_j < t_{\max}, \quad j = 1, 2, 3, 4. \tag{2}$$

The dynamic model of the system can be expressed through Lagrange's approach [11]. The equation can be given as

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\theta}_i}\right) - \frac{\partial L}{\partial \theta_i} = \boldsymbol{\tau}_i, \qquad i = 1, 2 \tag{3}$$

where $L$ is Lagrangian, $\theta_i$ are the generalised joint variables, and $\boldsymbol{\tau}_i$ are the externally applied torque at the joint or generalised forces. In general for a $nDOFs$ system with $m$ actuated cables, the joint torques can be expressed as $\boldsymbol{\tau}_i = \boldsymbol{\tau}_i^c$. In a cable-driven mechanism, the generalised force contribution of the cables is

$$\boldsymbol{\tau}_i^c = \sum_{j=1}^{4} \left(\hat{u}_j \cdot \frac{\partial \bar{r}_j}{\partial \theta_i}\right) t_j \tag{4}$$

where $\hat{u_j}$ is the unit vector along the $j^{\text{th}}$ cable, $\bar{r}_j$ is the position vector of its attachment point, and $t_j$ is the cable tension.

Arranging the cable contributions for all generalised coordinates in matrix form yields

$$\mathbf{A}_L \boldsymbol{T}_L = \boldsymbol{\tau}_L \tag{5}$$

where

$$\mathbf{A}_L = \begin{bmatrix} \hat{u}_1 \cdot \frac{\partial \bar{r}_1}{\partial \theta_1} & \hat{u}_{22} \cdot \frac{\partial \bar{r}_2}{\partial \theta_1} + (\hat{u}_{21} - \hat{u}_{22}) \cdot \frac{\partial \bar{r}_1}{\partial \theta_1} & \hat{u}_{33} \cdot \frac{\partial \bar{r}_3}{\partial \theta_1} + (\hat{u}_{34} - \hat{u}_{33}) \cdot \frac{\partial \bar{r}_4}{\partial \theta_1} & \hat{u}_4 \cdot \frac{\partial \bar{r}_4}{\partial \theta_1} \\ \hat{u}_1 \cdot \frac{\partial \bar{r}_1}{\partial \theta_2} & \hat{u}_{22} \cdot \frac{\partial \bar{r}_2}{\partial \theta_2} & \hat{u}_{33} \cdot \frac{\partial \bar{r}_3}{\partial \theta_2} & \hat{u}_4 \cdot \frac{\partial \bar{r}_4}{\partial \theta_2} \end{bmatrix} \tag{6}$$

$$\boldsymbol{T}_L = \begin{bmatrix} t_1 \\ t_2 \\ t_3 \\ t_4 \end{bmatrix} \tag{7}$$

$$\boldsymbol{\tau}_L = \begin{bmatrix} \tau_1^c \\ \tau_2^c \end{bmatrix} \tag{8}$$

Here:

- $A_L$ is the generalised structure matrix,
- $T_L$ is the cable tension vector,
- $\tau_L$ contains inertia terms and all external forces other than cable forces.

A cable-driven system is tensionable if and only if:

1. $\mathbf{A}_L$ is full rank,
2. There exists a vector in the null space of $\mathbf{A}_L$ whose components corresponding to cable tensions are all of the same sign.

**Boundaries of the Tensionable Workspace** To determine whether a given configuration of the cable-driven system is tensionable, various methods are proposed [19], but the null-space approach is adopted [20]. The analysis is based on the generalised equilibrium equation expressed as

$$\mathbf{A}_L \boldsymbol{T}_L = \tau_L \tag{9}$$

For tension in cable we have

$$\boldsymbol{T}_L = \mathbf{A}_L^+ \tau_L + \mathbf{n}_A z \tag{10}$$

where $\mathbf{A}_L^+$ is the Moore–Penrose pseudo-inverse of $\mathbf{A}_L$ and $\mathbf{n}_A$ is a vector in the null space of $\mathbf{A}_L$ and $z$ is scalar parameter[9].

The CDM system is tensionable if and only if:

1. $\mathbf{A}_L$ is full rank matrix
2. There exists a null-space vector $\mathbf{n}_A$ whose components are of the same sign.

### 2.2 Genetic Algorithm Framework

The geometry of a cable-driven manipulator plays an important role in determining its tensionable workspace. In a CDM, cables can only pull and not push, so at every configuration, the system must be able to generate the required joint torques while keeping all cables in positive tension. This depends on the cable attachment positions $(d, h)$ and actuator locations because these geometric parameters define the structure matrix A. Changes in attachment distance lead to changes in direction vectors of the cables, which change the null space of A. Since the tension distribution is obtained from Eq. (9), any variation in geometry alters whether a feasible positive tension solution exists. As a result, the boundaries of the tensionable workspace shift. A configuration that was previously feasible may become infeasible if the matrix A loses rank (singular configuration). Therefore, the tensionable workspace is highly sensitive to geometric parameters$(d, h)$.

Because of this strong nonlinear relationship between geometry and tension feasibility, the soft optimization approach using a Genetic Algorithm (GA) is adopted. The feasibility condition depends on null-space sign constraints, which makes the problem difficult to solve using traditional gradient-based methods. GA searches globally through a population of solutions and gradually improves the design by selection, crossover, and mutation. By encoding cable attachment parameters as design variables and defining workspace feasibility as the fitness function, GA helps us systematically explore different geometries and find an optimal configuration that maximises the tensionable workspace while satisfying all constraints. This makes GA a suitable and practical approach for our application.

**Design Variables** : The cable attachment parameters are defined as:

$$p = [d, h] \tag{11}$$

where $d$ is the distance of cable attachment from the joint center and $h$ is the distance from the cable attachment to the centerline of the link. These variables influence the cable structure matrix $A_k$ and the tensionable workspace. The bounds on the design variables d and h are selected based on the preliminary parametric study carried out before optimization. From this study, it was observed that the tensionable workspace reaches its maximum value only within a specific range of attachment distances and routing angles. The design constraints are given as

$$d_{min} \leq d \leq d_{max}, \qquad h_{min} \leq h \leq h_{max} \tag{12}$$

Any violation of these bounds is penalised during fitness evaluation.

**Static Equilibrium and Tension Feasibility** :

In practical applications, a cable-driven manipulator is required to follow specific motion trajectories depending on the task. For example, in a pick-and-place operation, the end-effector moves from point A to point B along a predefined path. In rehabilitation or assistive applications, the manipulator must follow repetitive joint-space trajectories. In this work, to evaluate the tension feasibility over representative task motions, two types of trajectories are considered straight-line path and square path in the workspace. These trajectories are divided into N sample points, and feasibility is checked at each configuration along the path. For each trajectory point $k$=1,. . . ,N, the static equilibrium condition must satisfy:

$$A_k T_k = 0 \tag{13}$$

where:

- $A_k \in R^{2\times 4}$ is the cable structure matrix,
- $T_k \in R^4$ is the cable tension vector,

Since the system is redundantly actuated, the general solution is:

$$T_k = N_k z \tag{14}$$

where

- $N_k$ is null space basis of $(A_k)$
- $z$ is a scalar parameter.

The null-space component allows redistribution of internal cable tensions without affecting torque equilibrium. A configuration is considered feasible if:

$$N_k z > 0 \tag{15}$$

for some scalar $z$ singularity avoidance requires:

$$\operatorname{rank}(A_k) = 2 \tag{16}$$

**Objective Function** : The optimization objective is to minimize trajectory infeasibility:

$$J(p) = \frac{1}{N}\sum_{k=1}^{N} p_k + \alpha_{max}\max_k(p_k) \tag{17}$$

where

$$p_k = \begin{cases} 0, & \text{if feasible tensions exist,} \\ M, & \text{otherwise,} \end{cases}$$

- $M$ is a large penalty constant
- $\alpha_{max}$ is the weight for worst-case infeasibility.

The final optimization problem solved using the Genetic Algorithm is

$$\min_{p} \left( \frac{1}{N} \sum_{k=1}^{N} p_k + \alpha_{\max} \max_{k}(p_k) \right),$$

where $N$ is the number of trajectory points and $\alpha_{\max}$ is a weighting factor that penalizes the worst-case infeasible configuration.which is subject to

$$A_k T_k = 0, \quad T_k > 0, \quad \mathrm{rank}(A_k) = 2$$

This formulation guarantees that the optimized cable geometry *(d, h)* enables the robot to generate the required joint torques across the entire trajectory while maintaining bounded, physically feasible cable tensions.

The overall Genetic Algorithm (GA) procedure follows the flowchart shown in Fig. 2 and is summarised as follows. In the initialisation stage, the required joint trajectories $(\theta_1, \theta_2)$ are loaded. The appropriate bounds are set for the design variables $d$ and $h$, which are based on a parametric study. The GA control parameters, such as population size, crossover rate, mutation rate, and maximum number of generations, are also initialised. Each chromosome in the population represents a candidate cable attachment configuration and is encoded as a vector $\mathrm{p} = [d, h]$.

During fitness evaluation, each chromosome is evaluated by checking its tension feasibility along the entire trajectory. For every trajectory point k, the structure matrix $A_k$ is computed, and its rank is verified to avoid singular configurations. The particular tension solution $N_k z$ is evaluated to find whether all cable tensions remain positive or not.

If the configuration is feasible, the penalty value $p_K$ will be zero; otherwise, a large penalty is assigned. The total objective value $J(p)$ is then computed by summing the penalties for all trajectory points. A lower objective value results in the best feasibility performance. After the fitness evaluation, the better chromosomes are selected for the next generation. The selection is based on fitness values, meaning that solutions with lower cost will be chosen. In simple terms, better designs are more likely to be selected and produce new designs.

In the crossover stage, two selected parent chromosomes exchange their design variables to create new offspring. For example, the value of d from one parent can combine with the value of h from another parent. This helps the algorithm explore new combinations of cable attachment geometry. After crossover, mutation is applied in mutation small random changes are added to the variables d and h. This step is involved because it prevent the algorithm from getting stuck at a local solution and help in exploring the design space more effectively.

The GA process continues for multiple generations. The algorithm stops when the fitness value becomes very small. The best chromosome obtained at the end of the process represents the optimal cable attachment parameters $p = [d, h]$ After the optimization is completed, post-processing is carried out to verify the results. The entire trajectory is checked again to confirm tension feasibility.

To evaluate workspace analysis, two representative end-effector trajectories are considered a straight-line path and a square path. The geometric parameters

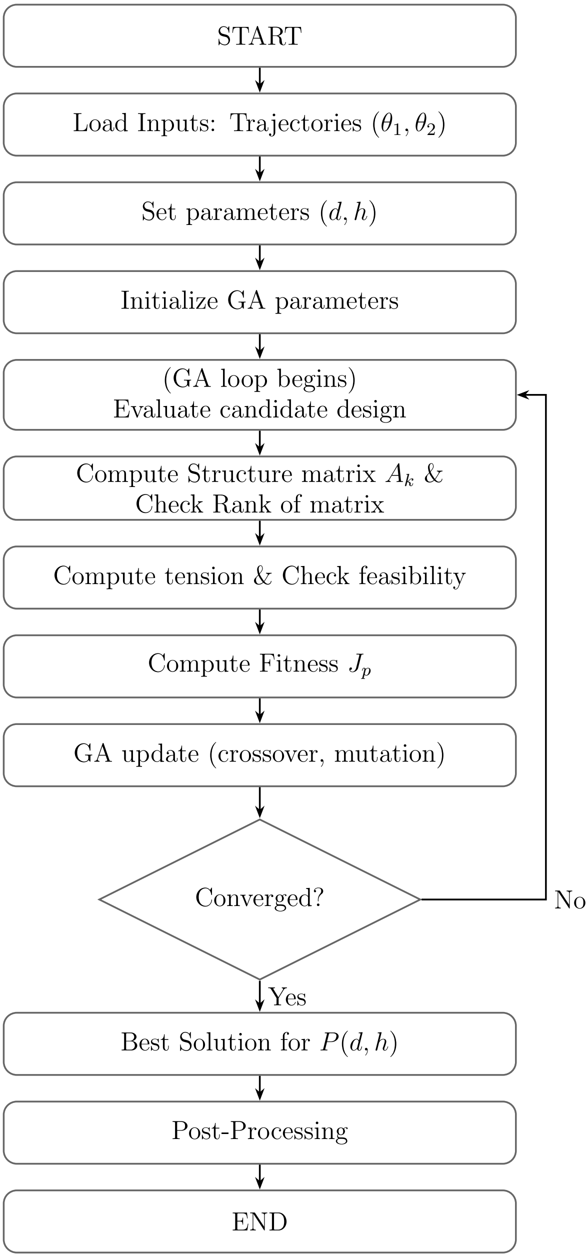



Fig. 2: Genetic Algorithm Flow Chart

of the CDSM are used as the design inputs listed in Table 1 for the Genetic Algorithm (GA). The manipulator consists of two identical links, and the cable attachment parameters are treated as design variables. The attachment distances $d$ and offset $h$ are defined as percentages of the corresponding link lengths. The trajectories are used to determine whether configurations are within the the resulting tensionable workspace. The GA explores different combinations of normalized attachment parameters to identify configurations that maximise the tensionable workspace.

Table 1: Design Parameters Used as input in Genetic Algorithm

| **Parameter** | **Value / Range** |
|---|---|
| Link length ($L_1$) | 10mm |
| Link length ($L_2$) | 10mm |
| Cable attachment distance ($d$) | $0.5\%L$ – $0.9\%L$ |
| Cable offset ($h$ ) | $0.2\%L$ – $0.6\%L$ |

Table 2: Genetic Algorithm Parameters Used in the Optimization

| **Parameter** | **Value** |
|---|---|
| Population Size | 120 |
| Maximum Generations | 50 |
| Elite Count | 2%of population |
| Crossover Probability | 0.8 |
| Selection Strategy | Stochastic Uniform Selection |
| Mutation Strategy | Adaptive Feasible Mutation |

The Genetic Algorithm was implemented with a population size of 120 individuals and executed for 50 generations. A crossover probability of 0.8 was employed. Selection and mutation were performed using MATLAB's default GA operators. Elitism was incorporated by preserving 2% of the best individuals in each generation.

## 3 Results and Discussion

This section represents the results obtained by workspace analysis of CDM. In the GA, the design variables representing the cable attachment parameters $(d, h)$ are considered as chromosomes. For each chromosome, the cable attachment geometry is used to compute the structure matrix $A_K$ using Eq 13. The system is redundantly actuated, and the cable tension solution is calculated using the null-space formulation (Eq.14). For each configuration, the computed tension values are checked to ensure that all cable tensions are positive, as cables can only pull. If a positive tension solution exists, then the configuration is considered feasible. The fitness of each GA individual is then evaluated based on the number of feasible configurations along the trajectories, so cable attachment parameters will maximise the tensionable workspace.

### 3.1 Square Trajectory

Square trajectories are commonly used in industrial robotic tasks such as pick-and-place operations, surface inspection, and planar machining. In this study, the square trajectory is defined in the Cartesian space of the manipulator and sampled at discrete points along the path. For each point on the trajectory, the corresponding joint angles were obtained using inverse kinematics, and the structure matrix $A_K$ was computed based on the cable attachment geometry. The results obtained from the GA-optimized parameters were evaluated along the circular path, and the feasible configurations were identified.

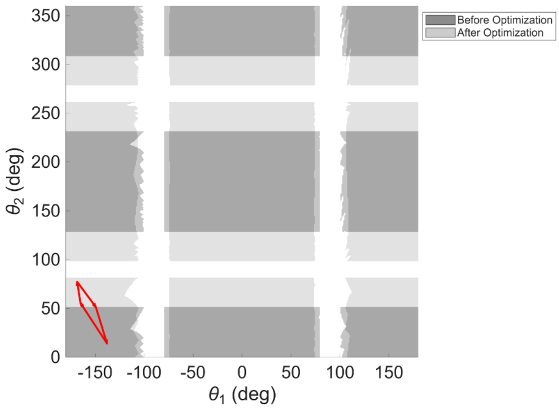
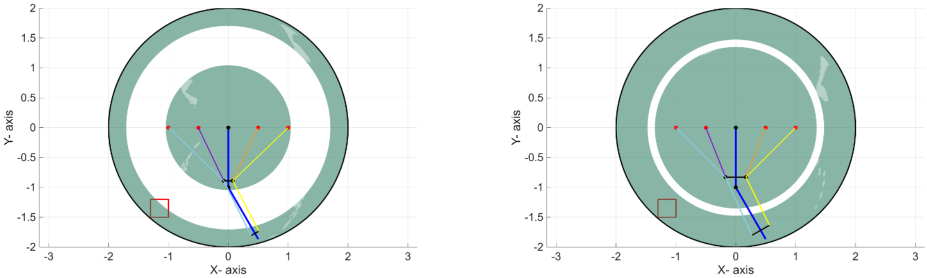



Fig. 3: Joint space tensionable workspace for square trajectory

Figures 3 and 4 show the corresponding Joint space and the Cartesian space trajectory of the feasible configurations. Figs. 4 (a) and (b) highlight the changes in the workspace before and after optimization. The corresponding optimized values of $d$,$h$ are listed in Table 2.

Table 3: Parameters before and after GA Optimization *(in mm)*.

| **Parameter** | **Before Optimization** | **After Optimization** |
|---|---|---|
| $d$ (attachment distance) | 8.9 | 8.3 |
| $h$ (offset distance) | 1.5 | 2.4 |




(a) Cartesian workspace before optimization

(b) Cartesian workspace after optimization

Fig. 4: Cartesian workspace before and after GA optimization. The trajectory is inside the workspace after optimization. The manipulator pose, along with the motor position, is also highlighted.

### 3.2 Straight line Trajectory

A straight-line trajectory was also considered to evaluate the performance of the manipulator along a continuous linear motion. Straight-line motions occur in many applications, such as painting, cutting, and material handling, where the end-effector must move smoothly between two points. A straight path was defined in the Cartesian workspace and discretized into multiple points. For each point along the trajectory, the corresponding joint angles were calculated, and the structure matrix $A_K$ was calculated to evaluate the feasibility of cable tension using the null-space formulation. Only configurations that produced positive cable tensions were considered valid.

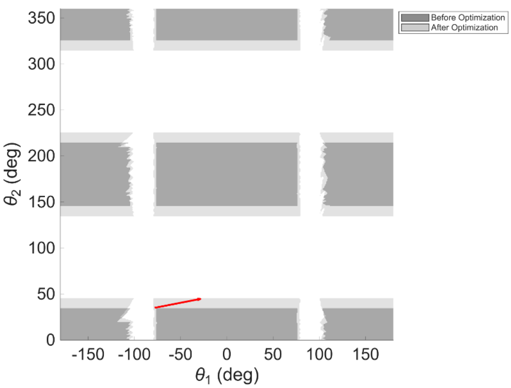
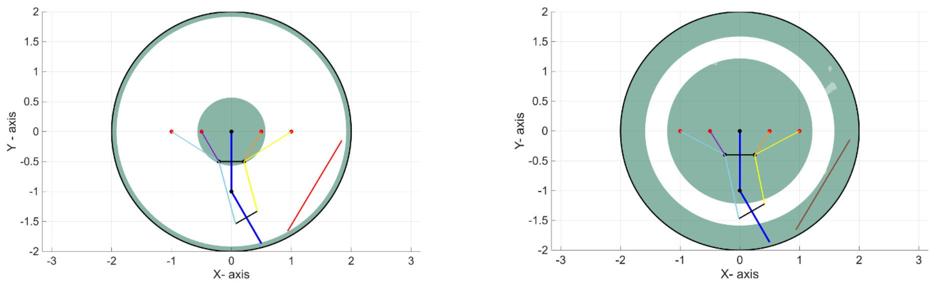



Fig. 5: Joint space tensionable workspace for line trajectory




(a) Cartesian workspace before optimization

(b) Cartesian workspace after optimization

Fig. 6: Cartesian workspace before and after GA optimization. The trajectory is inside the workspace after optimization. The manipulator pose, along with the motor position, is also highlighted.

Figures 5 and 6 show the corresponding joint space and the Cartesian space trajectory of the feasible configurations. Figs. 6 (a) and (b) highlight the changes in thr workspace before and after optimization. The corresponding optimized values of $d$,$h$ are listed in Table 3.

Table 4: Parameters Before and After GA Optimization in mm

| **Parameter** | **Before Optimization** | **After Optimization** |
|---|---|---|
| $d$ (attachment distance) | 4.2 | 6.1 |
| $h$ (offset distance) | 3.3 | 5 |

The simulation results highlight the effect of optimization of the cable attachment parameters on the tensionable workspace of the cable-driven manipulator. By adjusting the attachment distance $d$ and offset $h$ using the Genetic Algorithm, the feasible workspace region was improved compared to the initial configuration. The comparison of the Cartesian workspace before and after optimization, as shown in Figs. 4 and 6, shows that the optimized parameters allow a larger number of feasible configurations where all cable tensions remain positive, which can be used in the application accordingly. This study indicates that the cable attachment plays an important role in determining the workspace capability of the system.

The evaluation using two trajectories further highlights the practical applicability of the optimized design. The square trajectory, which represents motion patterns commonly used in industrial tasks, was able to maintain positive cable tension throughout the entire path after optimization. Similarly, the straight-line trajectory also showed improved feasibility with the optimized parameters. These results prove that the proposed GA optimization approach can identify cable attachment configurations that enhance the manipulator's operational workspace while keeping the tension positive for cable-driven systems.

## 4 Conclusion

In this work, a modeling and optimization framework was developed for analyzing a two-link cable-driven system. The system's tensionable workspace depends on the cable attachment parameters,, which affect the structure matrix. A null-space-based approach was used to evaluate whether feasible cable tensions exist at each configuration along a given trajectory. Two trajectories were considered: a square and a straight line trajectory. To improve the feasibility of cable tensions over this trajectory, a Genetic Algorithm (GA) based optimization framework was developed. The cable attachment parameters were treated as design variables, and the objective function was formulated to penalise infeasible configurations along the trajectory while satisfying positive tension and avoiding singularities. The GA approach was chosen because the feasibility-based objective function is nonlinear and discontinuous, making it difficult to apply traditional optimization methods. The results proveprove that the selecting the cable attachment geometry through GA improves the tension feasibility. The optimized configuration ensures that positive tension across the entire trajectory.

In future, the proposed Genetic Algorithm framework can be integrated with machine learning to reduce computational time and improve search efficiency. Further, the approach can be extended to manipulators with higher degrees of freedom with complex cable routing and motor positions.

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