Influence of payload and platform dimensions on the static workspace of a 4-cable driven parallel robot

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Abstract—**This paper presents the influence of payload and platform dimensions on the static equilibrium workspace of an under-constrained cable-driven robot with four cables taking into account the forces and the moments due to the forces acting on the moving platform. The problem is formulated as a non-linear optimization problem with maintaining static equilibrium as the objective function. The simulations are done in MATLAB. The maximum force on the cables, the payload acting on the platform and the dimensions of the moving platform are varied and their corresponding effects on the static equilibrium is studied. The obtained results are analyzed to finalize the design of the collaborative cable-driven robot to be installed in existing production lines for the agile handling of parts in a manufacturing industry.**

Index Terms—**Static Equilibrium, non-linear optimization, cable-driven parallel robot.**

I. INTRODUCTION

Cable-Driven Parallel Robots (CDPRs) belong to the class of parallel manipulators in which the rigid links of the robot is replaced by a set of cables driving a platform with the help of a winch consisting of a tensioning motor and spool or a linear actuator moving a pulley system [1]. The position and orientation of the moving platform are controlled by the coordinated retraction and extension of the cables. CDPRs are very well suited for a number of applications like large-scale material handling and manufacturing process, building construction, rescue operations, aerial cameras, high-speed assembly and pick and place operations and so on [2] because of a number of desirable features such as such as simple structure, large load capacity, high payload-to-weight ratio, and low inertia, compared to serial-link and other parallel type robots [3]. Several classifications of CDPRs are available in the literature

[3]. According to the classification suggested by Cone [4] and Verhoeven [3] there are mainly three types of CDPRs namely over-constrained, fully-constrained and under-constrained. A cable robot with m-cables and n-degrees of freedom is said to be completely restrained or fully-constrained if it has one cable more than the number of degrees of freedom, i.e. $m = n+1$. In such a type of arrangement, all degrees of freedom can be controlled through the cables. An over-constrained CDPR has the condition $m \geq n+1$. An incompletely restrained or under-constrained cable robot is one in which the number of cables is less than or equal to the number of degrees of freedom, i.e. $m \leq n$. Such systems have one feasible solution for cable tensions and mostly rely on gravity for keeping the cables taut.

In order to decrease complexity, cost, set-up time, likelihood of cable interference etc., it is advantageous to use CDPRs with a limited number of cables in several industrial applications in which the task to be performed requires a limited number of controlled freedoms or a limitation of dexterity is acceptable [5]. Several studies are available on under-constrained CDPRs [6]–[8]. Some important results on the stability analysis and kinematics of under-constrained parallel robots have been discussed by Merlet and Daney [9], Carricato and Merlet [10].

The major objective of the project is to design a collaborative cable-driven parallel robot to be installed in the existing lines of a manufacturing industry where available space is reduced by already installed machines. Hence, a cable-driven parallel robot with 4 cables is proposed as a solution. The number of cables is restricted to 4 for the ease of installation with simple anchor points in the environment and also to reduce the complexity of cable collision with the equipment installed on the shop floor. It is desired to have the actuators on the moving platform, unlike other designs in which the

motors are placed in the base or fixed structure.

This paper presents the preliminary studies carried out to help the user in fixing the dimensions of the moving platform and the limits on the cable tension and the platform orientation by analyzing the available static equilibrium workspace for various configurations. The results from this study will help the designer in selecting the appropriate motor and its corresponding elements, the arrangement of cables according to the cable tensions, and the weight of the platform according to the payload. It will also give the an idea about the various regions where the robot performance is satisfactory and acceptable. Earlier works with such CDPRs take into account only the forces acting on the moving platform (point-mass). However, this work takes into account both the forces and the moments due to the forces acting on the moving platform with a given dimension. The results obtained from this study indicate that it is possible to achieve satisfactory results with 4 cables and the results obtained can be used in finalizing the parameters for the design of the CDPR.

II. KINEMATIC AND GEOMETRIC MODELING

The unilateral constraints imposed by the cables prevents the application of the modeling and analysis methods developed for conventional rigid link parallel manipulators to the cable-driven robots. The equations used in the modeling of CDPR are presented in this section [2]. A general cable-driven parallel robot with m-cables is shown in fig. 1.
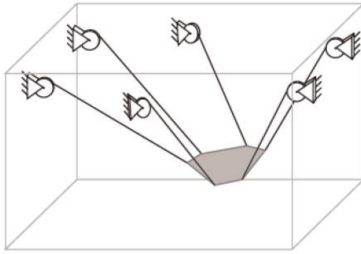

Fig. 1. A simple arrangement of a CDPR

The following assumptions are made to reduce the complexity of computation 1) The mass of the cables is negligible and the cables are non-elastic. 2) The moving platform is assumed to be a rigid body defined by its mass and inertia matrix. 3) The cable is assumed to be taut between points and is considered to be a straight segment.

As seen in fig. 2, a fixed reference frame also known as the base frame is attached to the base of a CDPR. A moving reference frame is attached to the moving platform and contains the point P to be positioned by the mechanism. The orientation of the moving frame with respect to the base frame is given by the rotation matrix Q. Also, from fig. 2, a_i and b_i are respectively defined as the vector connecting point O to point A_i and the vector connecting point P of the
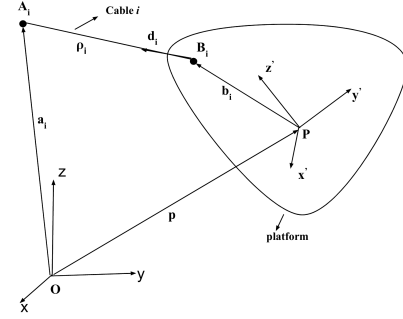

Fig. 2. Kinematic model of a CDPR

platform to the point B_i, both vectors being expressed in the base frame. The position p of the mobile platform is given by $\overrightarrow{OP}$.

The loop closure equations are first developed for each chain of the CDPR to identify the kinematic relationship between the cable space and body space for a CDPR. The length of the cable can be calculated by using the vector loop equation given by

$$\overrightarrow{d_i} = \overrightarrow{a_i} - \overrightarrow{b_i} - \overrightarrow{p} \tag{1}$$

where, $\overrightarrow{d_i}$ is the vector along cable i pointing from B_i to A_i and $(i = 1, 2, ., .m)$. The length of the cable is calculated using

$$\rho_i = \|\overrightarrow{d_i}\|^2 \tag{2}$$

Also using eq. 2, the unit vector can be calculated by

$$\hat{d}_i = (\overrightarrow{a_i} - \overrightarrow{b_i} - \overrightarrow{p})/\rho_i \tag{3}$$

This basic model has been established in the early works on CDPRs and is purely based on the geometric analysis. This equation(eq. 3), however, does not take into account the ability of the mechanism to maintain the tensions in the cables. In order to address this issue, the concept of wrench matrix was introduced where statics of CDPR is considered.

When a tension t_i is applied, the cable i exerts at point B_i, a pure force $t_i\hat{d}_i$ on the mobile platform. This pure force generates a moment $\overrightarrow{b_i} \star t_i\hat{d}_i$ at the reference point P of the mobile platform and the wrench (force/moment pair) applied at P by the ith cable is $t_i w_i$ with the wrench w_i defined as

$$w_i = \begin{bmatrix} \hat{d}_i \\ \overrightarrow{b_i} \star t_i\hat{d}_i \end{bmatrix} \tag{4}$$

If w_p is the total wrench applied at point P by the m-cables then the relationship between the tensions in the cables and the wrench is written in matrix form as

$$W \overrightarrow{t} = w_p \tag{5}$$

where, $\overrightarrow{t}$ is the vector of cable tensions and W is the $6*m$ pose dependent wrench matrix.

Most of the analytical results proposed in the literature are based on this equation. By properly defining the vector w_p, different solutions can be obtained to understand the workspace of CDPRs.

III. Workspace Analysis

The workspace analysis of cable driven robots is done taking into account the statics of the manipulator along with the change in cable lengths. There are many definitions available for workspace. The workspace of a CDPR is the set of position and orientation in which [11] 1) The end-effector is controllable, 2) The tensions in the cables are positive, 3) The force values lie between a minimum and a maximum in order to avoid the cables break or become slack, 4) The end-effector is far from singularities, and 5) Cable wrapping is avoided.

Different types of workspaces have been defined and addressed in the literature. The current work however presents the static equilibrium workspace of the cable robot to be designed. The static equilibrium workspace (SEW) is defined as the set of postures (position and orientation of the end-effector) that the end-effector can attain statically (only taking gravity into account). It is important to have a good knowledge about SEW as it will help in the appropriate determination of the design parameters (motor speed, platform dimensions etc.).

In order to calculate the SEW of the CDPR, the static equilibrium condition of the cable robot is used to find the force on each cable. In other words, the equations given below which indicate the sum of forces ($\sum F_i, i = x, y, z$) acting on the moving platform along the x, y, z direction and the sum of moments ($\sum M_i, i = x, y, z$) acting on the moving platform along the x, y, z direction respectively, needs to be satisfied to achieve static equilibrium.

$$\sum F_x = 0, \sum F_y = 0, \sum F_z = mg \qquad (6)$$

$$\sum M_x = 0, \sum M_y = 0, \sum M_z = 0 \qquad (7)$$

The only external force acting on the platform is the gravitational force (along with the mass of the platform and payload acting at the center of mass of the moving platform) and all other external forces and moments will not be discussed in this paper. The equations described above are formulated as a nonlinear optimization problem and is solved using fsolve in MATLAB with static equilibrium condition as the objective function.

IV. Results and Discussion

The results of the simulation carried out in MATLAB are presented in this section. The SEW of the CDPR inside a room of dimension $5m * 5m * 3m$ is presented in the figures below. The constraints on the angle of inclination of the moving platform about $x - axis$ and $y - axis$ were fixed at $\pm 30°$. The center of mass (CoM) of the moving platform was considered to be at a height of 0.2m below the cable attachment points while the CoM of the payload was considered at a height of 0.4m below the CoM of the platform. The step size was fixed along x and y axis to 0.1.

The search for possible workspace value was fixed reduced to the region of ($0.3 < x < 4.7, 0.3 < y < 4.7, 0 < z < 2.5$). The points were checked to see if they were belong to in the SEW by fixing various limits for the cable tension and payload of the platform as explained below. The dimensions of the platform were first varied and the corresponding percentage of SEW is presented in table I. The maximum tension on the cables for this study was set to be at 500N while the minimum tension was 1N . Since the final design includes the actuating motors on the moving platform, a dimension of $0.5m * 0.5m$ is considered to be a good compromise.

TABLE I
% OF SEW FOR PLATFORM WITH DIFFERENT DIMENSIONS

Platform dimensions(m)	$0.5 * 0.5$	$0.75 * 0.75$	$0.6 * 0.4$	$0.8 * 0.6$
SEW%	58	48	58	46

Since a 4 cable-driven spatial parallel robot has 4 degrees of freedom (the position x, y, z and one angle) that can be controlled by the cables, it is important to have an idea about how the platform orientation behaves as the simulation is done for static equilibrium condition.
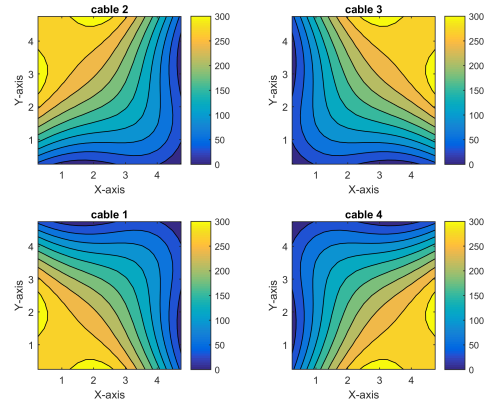

Fig. 3. Tension distribution (N) in 4 cables for z=1.5m for a payload of 30kg (20kg mass of platform + 10kg mass of the payload material)
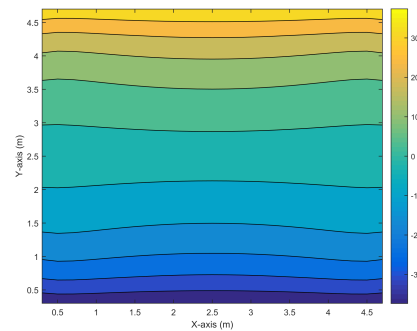

Fig. 4. Variation of angle (in degrees) about x-axis for z=1.5m

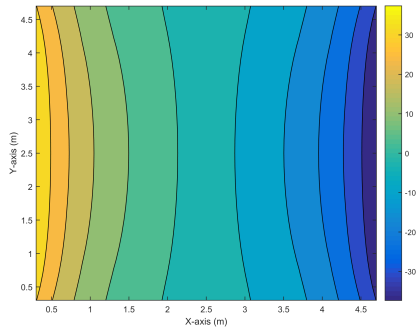Fig. 5. Variation of angle (in degrees) about y-axis for z=1.5m

The variation of cable tensions and the corresponding changes in the value of the angles about x-axis and y-axis when the moving platform is moving in a plane at the center of the room (z=1.5m) is shown in the figure below for a payload of 30kg (20 kg mass of the platform+10kg payload of the material) [12]. It can be seen that the change in angles about x-axis and y-axis is symmetrical under the consideration that the moving platform has equal length and width. The plot of cable tensions also exhibits symmetrical behavior with respect to x and y axis.

Following this, the weight of the platform was varied from 20kg, 25kg and 30kg respectively. The simulation was carried out to observe the SEW for two maximum cable tensions namely 500N and 300N respectively. The simulation results are presented in the figures below. It can be seen from the figures that for a platform weight of 20kg, the available SEW is higher than the ones obtained for the other platform weight (25kg and 30kg). The main objective is to give further information to designer in selecting the components for the design.
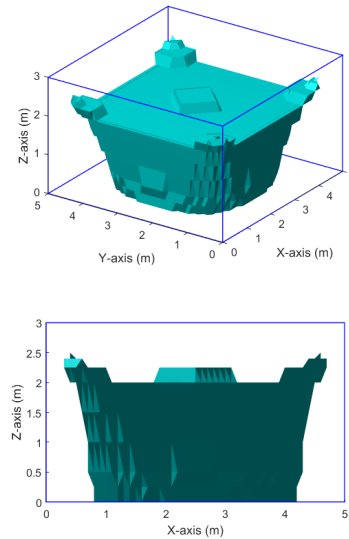

Fig. 6. SEW of the CDPR for a payload of 30kg (20kg platform+ 10kg payload) acting on the platform for a maximum force of 500N (a) 3-D representation and (b) XZ view of the workspace
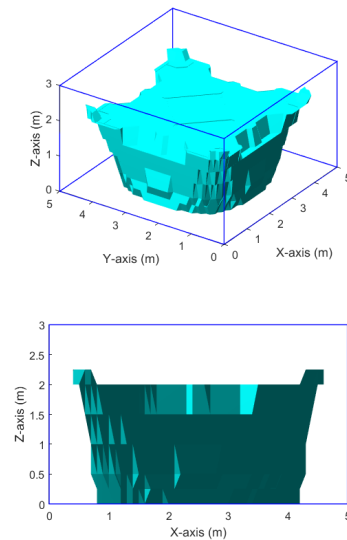

Fig. 7. SEW of the CDPR for a payload of 35kg (25kg platform+ 10kg payload) acting on the platform for a maximum force of 500N (a) 3-D representation and (b) XZ view of the workspace
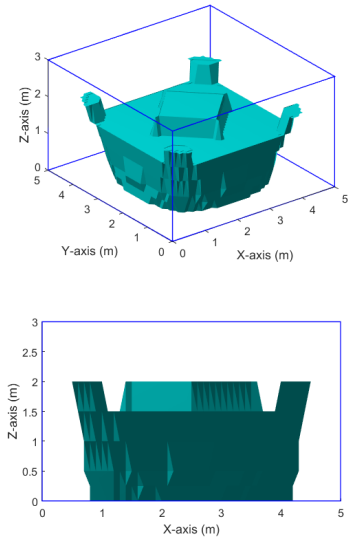
Fig. 8. SEW of the CDPR for a payload of 40kg (30kg platform+ 10kg payload) acting on the platform for a maximum force of 500N (a) 3-D representation and (b) XZ view of the workspace
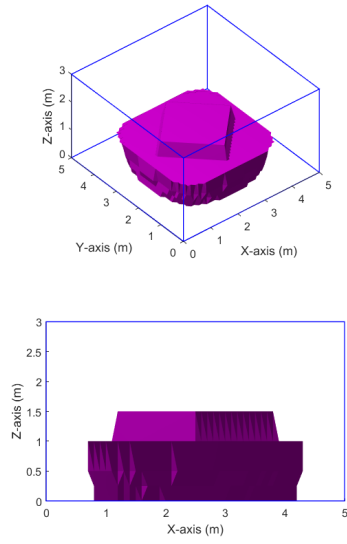

Fig. 10. SEW of the CDPR for a payload of 35kg (25kg platform+ 10kg payload) acting on the platform for a maximum force of 300N (a) 3-D representation and (b) XZ view of the workspace

Fig. 9. SEW of the CDPR for a payload of 30kg (20kg platform+ 10kg payload) acting on the platform for a maximum force of 300N (a) 3-D representation and (b) XZ view of the workspace

Fig. 11. SEW of the CDPR for a payload of 40kg (30kg platform+ 10kg payload) acting on the platform for a maximum force of 300N (a) 3-D representation and (b) XZ view of the workspace
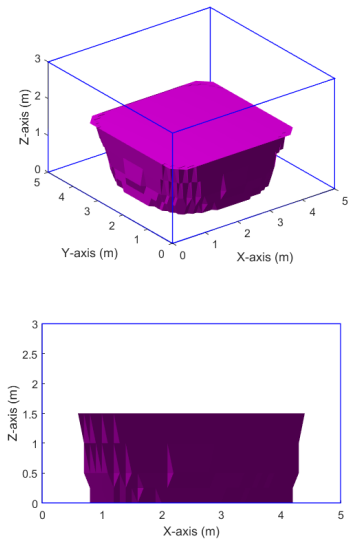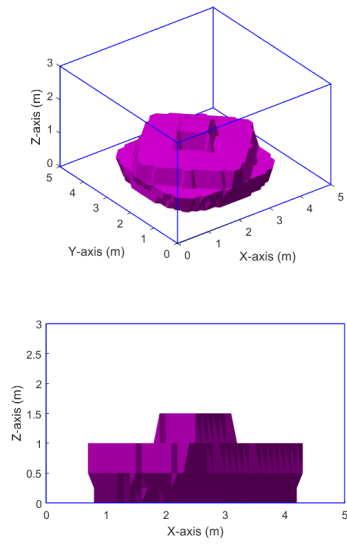
Following this, the CoM of the platform was varied from $0.2m\,to\,0.4m$ and the corresponding results obtained are shown in table II . It can be seen from the table that the SEW of the CDPR increases as the CoM of the platform is moved away from the cable attachment points. However, for the design to be done, the CoM is chosen to be 0.2m from the cable attachment points as the practical application of the other points will restrict the use of the CDPR for various heights.

TABLE II
% OF SEW FOR DIFFERENT CENTRE OF MASS FOR A PLATFORM OF
DIMENSION $0.5m * 0.5m$

Centre of Mass (CoM) in m	0.2	0.25	0.3	0.4
SEW%	58	65	72	73

V. CONCLUSION

The work presents the preliminary studies carried out in the design of a 4 cable-driven parallel robot. The static equilibrium workspace of the robot is calculated by varying the platform dimensions, payload and the corresponding tension limits for the cables. It can be seen that it is possible to have a sufficiently large workspace for such robots by limiting the orientation of the platform within a certain range and by making the appropriate choice of the dimension and payload. Future work will include the development of the dynamic model for the robot and implementation of the control law. The end final product of the current work is to have a prototype of the robot considered, in the agile handling of parts in a manufacturing environment.

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