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   3. Tension Distribution
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Introduction

Cable-driven parallel robots:

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</table>

Cable-driven parallel robots: applications

Displacement of heavy payloads in large spaces
Introduction

Cable-driven parallel robots: applications

Displacement of heavy payloads in large spaces

ANR COGIRO prototype

http://www.lirmm.fr/cogiro

CoGiRo

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Introduction

Cable-driven parallel robots: applications

Displacement of light payloads in large spaces

Skycam

LAR (Large Adaptive Reflector) - Canada

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Introduction

Cable-driven parallel robots: applications

Ultra High-Speed Robot FALCON
Kawamura et al., 1995

Max.: 43G, 13m/s

Displacement of objects with high velocities

IPANEMA
Robot DUISBURG

Université Laval,
Québec, Canada
(Cardou et al., 2014)
Introduction

Cable-driven parallel robots: applications

Rescue crane (Merlet and Daney, 2010)

Systèmes d’aide à la personne, de réhabilitation ou aisément transportable et déployable pour des opérations de secours en état d’urgence

Introduction

Cable-driven parallel robots: IRT JV proto 1

ACROBOT
Introduction

Cable-driven parallel robots: IRT JV proto 2

**Inverse Geometric Model**

- The inverse geometric model of a CDPR is quite simple. Given the pose of the moving platform, cable lengths are defined through linear equations.
- Cables are usually represented by massless linear segments.

\[
\begin{align*}
    l_i &= a_i^P - t - Rb_i^P \\
    \mathbf{d}_i &= \frac{l_i}{||l_i||_2} \\
    i &= 1, \ldots, m
\end{align*}
\]

- \( l_i \): \( i^{th} \) cable vector
- \( \mathbf{d}_i \): \( i^{th} \) cable unit vector
- \( a_i^P \): Exit point location for the \( i^{th} \) cable
- \( b_i^P \): Moving platform connection point location for the \( i^{th} \) cable
- \( t \): Cartesian coordinates of the moving platform CoM
- \( R \): Orientation matrix of the moving platform

**Static Equilibrium**

- The static equilibrium of the moving platform is described by linear equations.
- However, cable tensions are constrained to be positive \( \Rightarrow \) Semi-Algebraic Problem

\[
\mathbf{W} \tau + \mathbf{w}_e = 0
\]

- \( \mathbf{W} \): Wrench matrix
- \( \mathbf{W}^{-T} \): Pseudo-inverse of the wrench matrix
- \( \mathbf{w}_e \): External wrench
- \( \tau \): Cable tension vector
- \( \mathbf{n} \): Null space of the wrench matrix
- \( \lambda \): Vector of the null space multipliers
Direct Geometrico-Static Problem

Direct Geometrico-Static Problem #1

- The direct geometrico-static problem aims at defining the poses of a CDPR moving platform and the cable tensions required to assure its static equilibrium assuming that the lengths of the cables are known.

- Due to the unilateral nature of the kinematic constraints, cables can only pull the platform and not push it.

- The characteristics of the direct geometrico-static problem depend on:
  - The number of tensed cables and the DoF of the moving platform (the number of tensed cables may change according to the moving platform pose).
  - The cable model
Direct Geometrico-Static Problem #2

- CDPRs modeled with linear cables can be classified into:
  - Under-Constrained CDPRs: \( m < n \)
  - Fully Constrained CDPRs: \( m = n \)
  - Over-Constrained CDPRs: \( m > n \)

- The solutions of the corresponding univariate polynomial are:

<table>
<thead>
<tr>
<th>Number of Cables (m)</th>
<th>Number of equations</th>
<th>Number of Complex Solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 ((m = n))</td>
<td>6 Geometric</td>
<td>40</td>
</tr>
<tr>
<td>5 ((m &lt; n))</td>
<td>11 = 5 Geometric + 6 Static</td>
<td>128</td>
</tr>
<tr>
<td>4 ((m &lt; n))</td>
<td>10 = 4 Geometric + 6 Static</td>
<td>216</td>
</tr>
<tr>
<td>3 ((m &lt; n))</td>
<td>9 = 3 Geometric + 6 Static</td>
<td>156</td>
</tr>
</tbody>
</table>

References:


Direct Geometrico-Static Problem #3

- Over-constrained CDPR \((m > n)\) admit an infinite number of solutions in terms of cable tension distribution

- According to the architecture of the CDPR, some cables may be slack in certain moving platform poses.

- It is necessary to verify the presence of slack cables and to check whether the solutions to the direct-geometrico static problem are stable or not

- The direct-geometrico static problem of over-constrained CDPRs can be solved numerically or by means of interval analysis.

References:

Direct Geometrico-Static Problem #4

The sagging model is more accurate but the system of equations is not algebraic.

\[ \begin{align*}
E, A_0, \lambda_0, x_i, z_i, F_x, F_z, l_{0,i} \\
&\text{Young modulus} \\
&\text{Cable section} \\
&\text{Elastic cable coefficient} \\
&\text{Coordinates of the } i^{th} \text{ exit point} \\
&\text{Cable force components exerted on the platform by the } i^{th} \text{ cable} \\
&\text{Length of the unstrained } i^{th} \text{ cable}
\end{align*} \]


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Direct Geometrico-Static Problem #5

- Both the direct and the inverse geometrico-static problems of a CDPR with sagging cables can be solved numerically.

- The problem can be solved by means of interval analysis, supposing that only six cables are tensed.

- The problem admits several solutions, but some of them may not lead to a static equilibrium of the moving-platform.


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Direct Geometrico-Static Problem #6

- The direct geometrico-static problem can be solved using different methods, according to the ratio between $m$ and $n$ and the cable model. Existing methods are complex and time consuming. The solutions have to be analysed in order to verify whether they lead to a static equilibrium of the moving platform or not.

- **Open questions:**
  - Is it possible to compute all the moving platform poses which assure its static equilibrium for a CDPR with sagging cables?
  - Is it possible to develop a method to compute the feasible solutions of the Direct Geometrico-Static in real time?

Tension Distribution
### Tension Distribution

- Over-constrained CDPRs admit an infinite set of feasible solutions.

- Cable tensions can be adjusted in order to minimize the energy consumption of the CDPR ($\min |\tau|_2$) or to prevent cables from becoming slack ($\min |l|_2$).

- Cable tensions in CDPRs with massless cables can be minimised by using the null space of the wrench matrix.

\[ \tau = \tau_n + \tau_0 = W^t w_c + \lambda n \quad \tau \geq 0 \]


### Tension Distribution

- Cable tension distribution can be computed by means of alternative methods based on the analysis of two cable tension spaces:
  - The space of the **admissible cable tensions**.
  - The space of the **cable tensions** which assure the **static equilibrium** of the moving platform.

\[ \tau_1, \tau_2, \tau_3 \]

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Tension Distribution

Several methods have been proposed for CDPRs with linear cables:
- Barycentre Approach
- Closed-Form Method
- Corner Projection
- Puncture Method


Tension Distribution

Tension distribution in CDPRs with sagging cables can be performed by means of constraint optimization techniques.

The optimization problem aims at minimising the cable tensions while satisfying the kinematic and the static equilibrium constraints of the moving platform.

Geometric constraints:
\[ 0 < \| \mathbf{c}_j - \mathbf{b}_j \| < \ell \]
\[ 0 < \| \mathbf{c}_j - \mathbf{b}_j \| < \ell \]

Static equilibrium constraints:
\[ \sum \mathbf{R}_j \mathbf{F}_j \cdot \mathbf{L}_j = 0 \]
\[ \sum \mathbf{R}_j \mathbf{F}_j \cdot \mathbf{m}_j = 0 \]

Objective functions:
\[ f_1 = \| \mathbf{L} \| \quad f_2 = \| \mathbf{r}_j \| \]

Optimization problem:
\[ \min f_j(\mathbf{x}) \quad \text{such that} \quad \epsilon_j(\mathbf{x}) \leq \epsilon \]
Tension Distribution

- Several tension distribution techniques have been defined for CDPRs with linear cables. Each of them has several advantages and drawbacks in terms of tension minimization, solution continuity and time consumption.

- Is it possible to implement a tension distribution method for CDPRs with linear cables that provides feasible continuous solutions in real time, while minimising cable tensions?

Workspace Analysis
Workspace Analysis

- Since cables cannot push the moving platform, the static and dynamic equilibrium of the CDPR should be verified.

- The CDPR workspace, based on the moving platform static equilibrium, is defined as « Wrench Feasible Workspace » (WFW).

\[
\begin{align*}
\text{Static equilibrium:} & \\
\tau - \tau_m & = W \cdot \lambda_m \\
\lambda_m & > 0
\end{align*}
\]

\[
\begin{align*}
\text{Constraints:} & \\
\mathbf{f}_{\text{max}} & \leq \mathbf{f} \leq \mathbf{f}_{\text{max}}
\end{align*}
\]

\[
\begin{align*}
\text{WFW:} & \\
W & = \{ \mathbf{w} \mid \mathbf{f} \mathbf{e} \leq \mathbf{w}, \mathbf{f} \mathbf{e} \geq \mathbf{w} \}
\end{align*}
\]


Workspace Analysis

- The WFW is analysed by comparing the Available Wrench Set (AWS), and the Required Wrench Set (RWS).
- The AWS is a zonotope is an affine space generated by the linear mapping of the Available Cable Tension Set (ACTS), into the wrench space.
- The wrench feasibility can be analysed measuring the distances between the vertices of the RWS and the facets of the AWS.

Wrench feasibility:

\[
\begin{align*}
\mathbf{w}_d & \subseteq \mathbf{w}_a \\
\mathbf{C} \mathbf{w}_d & \subseteq \mathbf{d}, \ \forall \mathbf{w}_d \in \mathbf{w}_a
\end{align*}
\]
### Wrench Feasible Workspace (WFW)

System to solve: \[ F + w_e = 0 \]

- \( w_e \): Required Wrench set
- \( F \): Available Wrench

### Capacity Margin

An index measuring the degree of inclusion or exclusion of the required wrench set inside the available wrench set: the signed distance from each vertex of the required wrench set to each face of the available wrench set.

- Degree of Inclusion
  - \( s = 0 \)
  - \( s = + \) (Positive)
  - \( s = - \) (Negative)

---

How to compute these sets?

\[ W\dot{\mathbf{i}} + \mathbf{w}_e = 0_n \]

Available Tension Set \( \mathbf{i} \)

Available Wrench Set \( F \)

Available Tension Set \( \mathbf{i} \)

Available Wrench Set \( F \)

Required Wrench Set \( \mathbf{w}_e \)

The Polytopes of a CDPR

Available Tension Set \( \mathbf{i} \)

Available Wrench Set \( F \)

Required Wrench Set \( \mathbf{w}_e \)

Facet Representation \((a_k, b_k)\)

Vertex Representation

\( F_k = \{ \mathbf{w} \in \mathbb{R}^n: \mathbf{w} = -W\mathbf{i}, \mathbf{i} \in T_{n-1,k} \} \)

\( F_{k,1} = \{ \mathbf{w} \in \mathbb{R}^n: \mathbf{a}_k^T \mathbf{w} \leq b_k, k = 1, ..., q \} \)

\( w_e \equiv \begin{bmatrix} f_e \\ (1/r) n_e \end{bmatrix} \)

\( n \times 1 \)

\( m \times 1 \)

\( n (\text{DOFS}) \times m (\text{number cables}) \)

\[ W = \begin{bmatrix} c_1 & \cdots & c_m \\ \frac{1}{r_1} r_1 \times c_1 & \cdots & \frac{1}{r_m} r_m \times c_m \end{bmatrix} \]

Stéphane CARO
Computation of Index “s” (Minimum Degree of Constraint Satisfaction for each pose)

Distance from vertex $r$ (Required Wrench Set) to face $l$ (Available Wrench Set):

$$s_{r,l} = \left( \frac{b_1}{\|a_1\|^2} \frac{a_1 - w_{r,r}}{\|w_{r,r}\|^2} \right)^T \left( \frac{a_1}{\|a_1\|^2} \right)$$

$$= \frac{1}{\|a_1\|^2} \left( b_1 - w_{r,r}^T a_1 \right)$$

Minimum distance:

$$s = \min_{r=1..h} \left( \min_{l=1..q} s_{r,l} \right)$$

Where $h$ is the total number of vertices, and $q$ the total number of faces.

Workspace Analysis

Analysis of Robots Actuated through Cables by Handy and Neat Interface Software - ARACHNIS

Workspace Analysis

"Wrench Feasible Workspace"
(s = 0)

Workspace Analysis

"Wrench Feasible Workspace"
(coupe y=K)
Workspace Analysis

Interference-Free Constant Orientation Workspace

Workspace Analysis

Free-Interference Constant Orientation Workspace
Workspace Analysis

The CDPR workspace, based on the moving platform kinematic constraints, is defined as « Twist Feasible Workspace » (TFW).

Kinematic constraints:  
\[ J_1 - p = J_1 - \frac{t}{\omega_2} = 0 \]

Twist feasibility:  
\[ |p|_r \subseteq |p|_r \]

Constraints:

\[ t_{\text{max}} \leq t \leq t_{\text{max}} \]
\[ \theta_{\text{min}} \leq \theta, \theta, \theta \leq \theta_{\text{max}} \]

TFW:

\[ \forall p \in |p|, \exists \tilde{p} \in |p| \text{ s.t. } J_1 - p = 0 \]


Workspace Analysis

The CDPR workspace, based on the moving platform dynamic equilibrium, is defined as « Dynamic Feasible Workspace » (DFW).

Dynamic equilibrium:  
\[ W_T + A_p = 0 \]

Dynamic feasibility:  
\[ W_{T_r} \subseteq W_{T_r} \]

Constraints:

\[ t_{\text{min}} \leq t \leq t_{\text{max}} \]
\[ \theta_{\text{min}} \leq \theta, \theta, \theta \leq \theta_{\text{max}} \]

DFW:

\[ \forall p \in |p|, \exists \tilde{p} \in |p| \text{ s.t. } W_T + A_p = 0 \]

Workspace Analysis

- The wrench feasibility analysis leads to interesting results. However, the WFW can be computed only by discretizing the prescribed workspace of the CDPR or by means of interval analysis.
- Is it possible to develop an analytical tool to compute the exact boundaries of the WFW?

- The IDFW supposes that the twist of the moving platform is constant.
- Is it possible to analyse the dynamic feasibility of a CDPR supposing that the moving platform can assume a range of user-defined twists?

- The workspace of CDPRs has been formally defined for linear cable models.
- How can we represent mathematically the wrench feasibility conditions for CDPRs with sagging cables?

Stiffness modelling
Stiffness Modelling #1

- The elasto-static model of CDPRs are defined according to the cable model describing the CDPRs.
- An accurate geometric model of the CDPR may include the influence of pulleys in the platform pose.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Cable Mass</th>
<th>Pulleys</th>
<th>Task Space</th>
<th>Cable Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roberts et al (1998)</td>
<td></td>
<td></td>
<td></td>
<td>Linear</td>
</tr>
<tr>
<td>Bruckmann et al (2010)</td>
<td></td>
<td>X</td>
<td></td>
<td>Linear</td>
</tr>
<tr>
<td>Gouttefarde et al (2014)</td>
<td>X X</td>
<td></td>
<td></td>
<td>Sagging</td>
</tr>
</tbody>
</table>


Stiffness Modelling #2

- According to the geometric model of the CDPR, several elasto-static models have been proposed in the literature. These models are valid for small displacements of the moving-platform.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Cable Mass</th>
<th>Pulleys</th>
<th>Task Space</th>
<th>Cable Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bezhadipour et al. (2005)</td>
<td></td>
<td></td>
<td>2T1R</td>
<td>Linear</td>
</tr>
<tr>
<td>Surdilovic et al. (2013)</td>
<td></td>
<td>X</td>
<td>3T</td>
<td>Linear</td>
</tr>
<tr>
<td>Arsenault et al. (2013)</td>
<td></td>
<td></td>
<td></td>
<td>Sagging</td>
</tr>
<tr>
<td>Gouttefarde et al. (2014)</td>
<td>X</td>
<td></td>
<td>3T3R</td>
<td>Sagging</td>
</tr>
<tr>
<td>Gagliardini et al. (2015)</td>
<td>X X</td>
<td></td>
<td>3T3R</td>
<td>Sagging</td>
</tr>
</tbody>
</table>

# Stiffness Modelling #3

The elasto-static models based on the linear cable model are computed according to the following differential form:

\[
\delta \mathbf{w} = \begin{bmatrix} \delta f \\ \delta \mathbf{m} \end{bmatrix} = \mathbf{K} \delta \mathbf{p} + \mathbf{K} \delta \mathbf{t}
\]

![Diagram](image)

- **Active Stiffness Matrix**
- **Passive Stiffness Matrix**

\[
\mathbf{K} = \sum_{i=1}^{m} \frac{\partial \mathbf{W}_i}{\partial \mathbf{f}} (\mathbf{W}_i \mathbf{F}_i) = \sum_{i=1}^{m} \frac{\partial \mathbf{W}_i}{\partial \mathbf{p}} \mathbf{F}_i + \sum_{i=1}^{m} \frac{\partial \mathbf{W}_i}{\partial \mathbf{t}} \mathbf{W}_i^T
\]

- \( \mathbf{K} \): Cartesian Stiffness matrix
- \( \delta \mathbf{w} \): Small variations in the external wrench
- \( \delta \mathbf{p} \): Small variations in the moving platform pose
- \( \delta \mathbf{t} \): Small variations in the moving platform position
- \( \delta \mathbf{r} \): Small variations in the moving platform orientation

---


# Stiffness Modelling #4

The elasto-static models based on the sagging cable model are computed referring to the following moving platform static equilibrium equation:

\[
\sum_{i=1}^{m} \left[ \mathbf{R}_i \mathbf{C}_{PM(b_i)} \mathbf{R}_i^T \right] \mathbf{F}_i - \mathbf{w}_i = 0
\]

\[
\mathbf{K} = \sum_{i=1}^{m} \frac{\partial \mathbf{W}_i}{\partial \mathbf{p}} \mathbf{F}_i = \sum_{i=1}^{m} \frac{\partial \mathbf{W}_i}{\partial \mathbf{r}} \mathbf{W}_i^T
\]

- \( \mathbf{W}_i \): Force projection matrix
- \( \mathbf{R}_i \): Cable reference frame orientation

---

Stiffness Modelling #5

- Simulation of a suspended CDPR with sagging cables:

![Stiffness Model with Sagging Effect (6 Cables CDPR, 100kg platform)](image)


Stiffness Modelling #6

- Simulation of a fully constrained CDPR with sagging cables:

![Stiffness Model with Sagging Effect (6 Cables CDPR, 100kg platform)](image)
Stiffness Modelling #7

- The elasto-static models of CDPRs with sagging cables have been computed following different procedures.
- Are those developed elasto-static models of CDPRs with sagging cables equivalent?
- The effect of pulleys on the elasto-static modelling of CDPRs with sagging cables has not been taken into account.
- Is it possible to express the elasto-static model of CDPR with sagging cables while considering the pulleys?
- Few research work focuses on the analysis of the elasto-static model of CDPR with large moving platform displacements.
- Which will be the best elasto-static model for large moving platform displacements?
Design of CDPRs #1

- The design of CDPRs intends to dimension the CDPR components and define its geometry.
- Several CDPR designs rely on the intuition of their designers.

Design of CDPRs #2

- In 2004, one of the preliminary trajectory-based design approaches has been proposed by Pusey et al. The design problem is formulated as an optimisation problem aiming at improving the size of the CDPR workspace.
- In 2008, Gouttefarde et al. proposed an optimal design strategy based on interval analysis.

Basic definitions of the Interval Analysis:

\[f([x]) = \{ f(x) \mid x \in [x] \leq [f]\}\]

Application to the Wrench matrix:

\[\forall x \subseteq [x], W(x) \subseteq [W]\]
Design of CDPRs #5

- Optimal design of a CDPR based on the dimensioning of the motors, the winches and the gearboxes. The optimization aims at maximising the size of the WFW and the TWF.

Problem definition:

\[
\begin{align*}
\text{maximize:} & \quad f(x) = p_f \\
\text{over:} & \quad x = [r_M, \Omega_M, \phi_w, r_B] \\
\text{subject to:} & \quad \forall \mathbf{p}_k \in \mathcal{P}: F_k = 1 \\
& \quad \delta_{ij} \geq \phi_c \quad \forall i, j = 1, \ldots, m, \ i \neq j \\
& \quad -\beta_{ij} \leq \delta_{ij}, \delta_{ij}, \beta_{ij} \leq \beta_{ij}
\end{align*}
\]

Optimal solution:

\[r_M = 1.44\text{Nm}, \Omega_M = 195.6\text{rpm}, \phi_w = 46.5\text{mm}, r_B = 3.1\]


Design of CDPRs #6

- Several CDPR design strategy have been proposed in the literature. Each strategy focuses on one or more components of the CDPRs.
- Is it possible to define a design strategy for CDPRs which aims at dimensioning all the components of a CDPR?
- Being the design problem formulated as an optimization problem, several optimisation algorithms have been tested?
- Which is the best optimisation algorithm to be used in order to solve the optimization problems associated to the design of CDPRs?
Reconfigurability

Design and Reconfigurability of RCDPRs #1

- Reconfiguration of CDPRs mostly focuses on the displacement of cable exit points.
- The main classification of RCDPRs is between:

  ![Continuous Reconfigurations](image1)
  ![Discrete Reconfigurations](image2)

Design and Reconfigurability of RCDPRs #2

- In continuous RCDPRs, exit points can assume a continuous set of possible locations.
- Planar RCDPR can be modelled and designed through an analytical optimisation.
- Spatial RCDPRs can be designed through a local numerical optimisation.

Design and Reconfigurability of RCDPRs #3

- Optimal design of a RCDPRs

References:

Design and Reconfigurability of RCDPRs #4

- In discrete RCDPRs, exit points can be located at a possibly large but finite number of locations.

![Diagram](image)

1186 selected configurations


Design and Reconfigurability of RCDPRs #5

- Validation of the reconfiguration strategy (external parts)

![Diagram](image)

# Design and Reconfigurability of RCDPRs #6

- Validation of the reconfiguration strategy (internal parts)


---

# Design and Reconfigurability of RCDPRs #7

- The design strategies based on analytical optimizations are limited to planar continuous RCDPRs.

- Can we define a full analytical description of a RCDPR behaviour to be integrated in the optimal design of spatial continuous RCDPRs?

- The design of discrete RCDPR is based on the analysis of a possible set of configurations. The procedure is time consuming and the choice of the set of possible configurations is performed by the designer.

- Is it possible to improve the performances of the proposed design strategy?

- Is it possible to define a new design strategy that does not rely on the experience of the designer?
Control

Control #1

- Control schemes are necessary to guide the CDPR and adjust its behaviour.
- They integrate several components, including:
  - The model of the CDPR.
  - The information provided by the internal and external sensors.
  - A moving platform trajectory generator.
  - A control law.

- CDPR control scheme and control law are inspired by the developments performed on serial and rigid-link parallel robots, including:
  - PID control.
  - Impedance control.
  - Adaptive control.

References:

Control #2

- Examples of control schemes.

![Dual-space adaptive control scheme with joint space controller](image)


Control #3

- Several control schemes have been proposed in the literature.

- Which is the best control scheme and the best control architecture, with respect a given task or a given CDPR design?

- Control schemes require to compute the model of the CDPR, verify the feasibility of the desired moving platform pose and provide an optimal distribution tension.

- How we can integrate all these aspects in the control scheme?

- Some research works propose to integrate external sensor in the control scheme.

- Which are the most efficient external sensors we can integrate in the CDPR design?
Conclusions

- CDPR have been widely investigated in the last two decades.

- Several advances have been performed in modelling, design and control of CDPRs.

- Lot of working prototypes have been built...

- ...but several open problems have not be solved, yet !!!
Communications

Original presentation by Stéphane CARO

Patents:

Journal articles:
- “Stiffness Model of Spatial Cable-Driven Parallel Robot with heavy Cables Considering the Influence of Pulleys”, ongoing

Workshops:

International Conference Articles:
Communications

International Conference Articles:


Design and Modeling of Cable-driven Parallel Robots: State of the Art and Open Issues

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