A Simple Control Strategy for Overconstrained Parallel Cable Mechanisms

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1. Introduction

From a practical point of view, the two most important advantages of parallel cable mechanisms over conventional parallel or serial mechanisms are their large workspace and their high load to weight ratio. These characteristics, hardly matched in robotics, allow large accelerations of the mechanism's moving platform over a large span. Using cables has also some disadvantages. As it can be seen in [1] and [2], because a cable can only exert a tension, the set of wrenches achievable by the platform is complicated to determine. Also, the precision on the pose of the platform can be reduced by the flexibility in the cables. The use of more cables than degrees of freedom (DOF) to obtain an overconstrained architecture can minimize these disadvantages. On the other hand, it induces internal forces that have to be controlled at the same time as the articular position. As seen in [3], this hybrid control is complex and technically demanding in practical implementations. In this document, we present a simple control strategy for overconstrained 6-DOF parallel cable mechanisms with $6 + n$ cables. We discuss how this strategy decouples the force and position control. A brief section describing a prototype that uses this control strategy is also included.

2. Dynamics

A schematic of an overconstrained cable mechanism is shown in figure 1 with $n = 3$. Such a mechanism can be used to position and orient a platform. We consider in our analysis that the cables are straight, rigid and weightless. With the previous assumptions, for a 6-DOF mechanism with $6 + n$ cables, the dynamics equations of the system in translation can be written as:

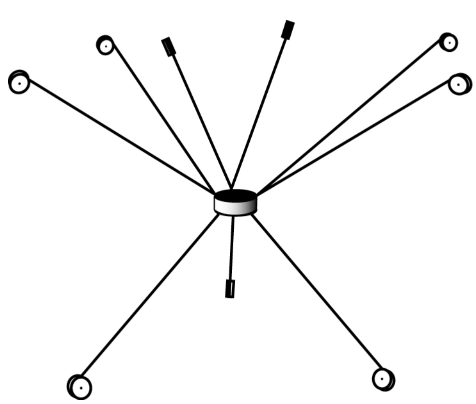

Figure 1. Overconstrained parallel cable mechanism.

$$\begin{bmatrix}\mathbf{u}_1\ \mathbf{u}_2\ \cdots\ \mathbf{u}_{6+n}\end{bmatrix}\mathbf{t} + \mathbf{f}_e = m\ddot{\mathbf{c}} \qquad (1)$$

where $\boldsymbol{t} = \begin{bmatrix}t_1 & t_2 & \dots & t_{6+n}\end{bmatrix}^T$, t_i being the tension in cable i, $\boldsymbol{u}_i$ a unit vector going along cable i from the platform, $\boldsymbol{c}$ the position of the center of mass of the platform, m its mass and $\boldsymbol{f}_e$ the external force vector acting on the platform.

The dynamics equations in rotation can be written as:

$$\begin{bmatrix}\mathbf{e}_1\ \mathbf{e}_2\ \cdots\ \mathbf{e}_{6+n}\end{bmatrix}\mathbf{t} + \boldsymbol{\tau}_e = \mathbf{I}\dot{\boldsymbol{\omega}} + \boldsymbol{\omega} \times \mathbf{I}\boldsymbol{\omega} \qquad (2)$$

where $\boldsymbol{e_i} = \mathbf{Q}\mathbf{b}_i \times \mathbf{u}_i$, $\boldsymbol{b}_i$ being the attachment point on the platform expressed in the frame attached to the platform, $\boldsymbol{Q}$ is the rotation matrix used to express vectors $\boldsymbol{b}_i$ in the fixed reference frame, $\boldsymbol{\omega}$ is the angular velocity vector of the platform, $\boldsymbol{\tau}_e$ is the external moment acting on the platform and $\boldsymbol{I}$ is its inertia matrix.

Combining expressions (1) and (2), the complete expression describing the dynamics of the system is:

$$\begin{bmatrix}\mathbf{u}_1\ \mathbf{u}_2\ \cdots\ \mathbf{u}_{6+n}\\ \mathbf{e}_1\ \mathbf{e}_2\ \cdots\ \mathbf{e}_{6+n}\end{bmatrix}\mathbf{t} = -\begin{bmatrix}\mathbf{f}_e\\ \boldsymbol{\tau}_e\end{bmatrix} + \begin{bmatrix}m\ddot{\mathbf{c}}\\ \mathbf{I}\dot{\boldsymbol{\omega}} + \boldsymbol{\omega}\times\mathbf{I}\boldsymbol{\omega}\end{bmatrix} \qquad (3)$$

$$\mathbf{G}\mathbf{t} = \mathbf{w}_e + \mathbf{w}_I \qquad (4)$$

where $\boldsymbol{w}_I$ is the vector of inertial forces and moments and $\boldsymbol{w}_e = \begin{bmatrix}\boldsymbol{f}_e\\ \boldsymbol{\tau}_e\end{bmatrix}$ is the wrench applied to the platform. This is an underdetermined system of equations that admits in general infinitely many solutions. In other words, infinitely many different sets of cable tensions (or equivalently saying winch torques sets) could produce a certain acceleration of the platform in the presence of a given external wrench. A typical hybrid (force and position) control strategy would use a criterion to chose between this infinity of possible sets. The control strategy that we propose instead is to position-control six cables and to force-control the rest of the cables. The first group of six cables are responsible for positioning and orienting the platform while the second group of n cables keeps a certain tension inside the system and increases the workspace. The control can be simplified even more if the n extra winches are given a command of applying a constant torque. Using this approach, the n extra cables act like constant force passive elements. The n extra winches simply wind and unwind to accommodate the movement of the platform induced by the first six cables. In that case, equation (4) becomes:

$$\begin{bmatrix}\mathbf{G}_p \ \mathbf{G}_f\end{bmatrix}\begin{bmatrix}\mathbf{t}_p \\ \mathbf{t}_f\end{bmatrix} = -\mathbf{w}_e + \mathbf{w}_I \qquad (5)$$

where $\boldsymbol{G}_p$ is a 6×6 submatrix composed of the first 6 columns of $\boldsymbol{G}$, $\boldsymbol{G}_f$ is a $6 \times n$ submatrix composed of the n last columns of $\boldsymbol{G}$, $\boldsymbol{t}_p$ comprises the first six elements of $\boldsymbol{t}$ and $\boldsymbol{t}_f$ its last n elements. Because $\boldsymbol{t}_f$ is a constant vector in the proposed control strategy, the equation can be rearranged as:

$$\mathbf{G}_p\mathbf{t}_p = -\mathbf{w}_e + \mathbf{w}_I - \mathbf{G}_f\mathbf{t}_f \qquad (6)$$

The system of equation is determined and can be solved in a straightforward manner to obtain a unique solution for $\boldsymbol{t}_p$, the tension that is theoretically necessary in the six position-controlled cables to obtain a certain platform acceleration under a certain external wrench.

3. Control Implementation

If our model of the mechanism was perfect and the external wrench was known, equation (6) could be used to control the tension in the cables with proper torques at the winches to produce a given desired trajectory $\boldsymbol{x}_d$. In practice, the model is never perfect and the wrench measure is seldom available. Hence, feedback must be utilized to follow closely a trajectory. Also, it is more convenient to measure the angular position of the winches than to measure the position of the platform directly. Equation (6) is thus adapted as a predictive term in a practical winch position-control strategy such as one shown in the block diagram of figure (2).

Because we do not know the external wrench, it is included in the "Robot" block of the diagram and taken out of equation (6) that becomes, after rearraging the terms:

$$\boldsymbol{\tau}_p = \frac{1}{r}\mathbf{G}_p^{-1}[\mathbf{w}_I - \mathbf{G}_f\mathbf{t}_f] \qquad (7)$$

where $\boldsymbol{\tau}_p$ is the desired torques at the six controlled winches to produce cable tensions $\boldsymbol{t}_p$ according to the dynamical model and r is the radius of the winches. The "IKP" block represents the inverse kinematics problem that translates the desired cartesian trajectory into a desired articular trajectory. The "Correction" block outputs a correction term that is added to the desirable torque given by the dynamical model. This term in our application is given by a PID such as:

$$\boldsymbol{\tau}_c = \ddot{\boldsymbol{\theta}}_d + k_p(\boldsymbol{\theta}_d - \boldsymbol{\theta}) + k_i\int(\boldsymbol{\theta}_d - \boldsymbol{\theta}) \qquad (8)$$

where $\boldsymbol{\theta}_d$ and $\boldsymbol{\theta}$ are respectively the desired and actual articular trajectories. Equations (7) and (8) are added to give $\boldsymbol{\tau}_w$, the torque command at the winches:

$$\boldsymbol{\tau}_w = \boldsymbol{\tau}_p + \boldsymbol{\tau}_c \qquad (9)$$

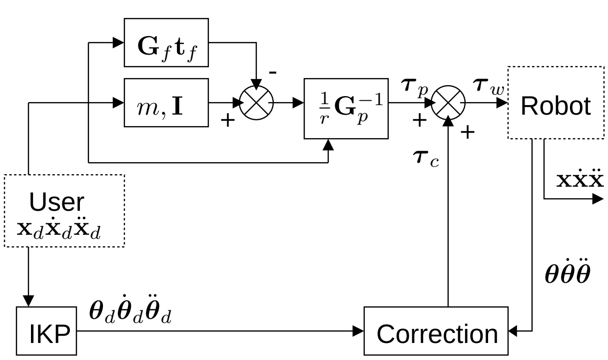

Figure 2. Block diagram of the control strategy.

4. Results and Discussion

The control strategy was used with a prototype having $n = 3$ extra cables such as one illustrated in figure (1). The three lower winches were applied a constant tension and the six upper ones were controlled to position and orient the platform. The low cost winches were equipped with optical encoders for the feedback and the cables used were kite strings.

The mechanism in itself and its control were thus really simple. As long as it would be within the tension limit of the upper cables, it would be equivalent to controlling a Gough-Stewart platform, which is a well-known problem. The use of the three lower cables in that manner increased the possible downwards acceleration. In fact, with that architecture without the lower three cables, the platform could not accelerate downwards with more than one g. With the three lower cables, an acceleration in that direction of $2.5g$ was attainable. It also enlarged the static workspace by keeping the upper cables in tension. By having the mechanism under tension, vibrations of the platform under acceleration are reduced and the positionning accuracy is increased. The accuracy of the positionning was measured with an optical sensor (Optotrak) to be at maximum $\pm 5mm$ across a static workspace of about $1.5m \times 1.5m \times 1.5m$.

The main disadvantage of such a mechanism compared to a hybrid-controlled one is that some external wrenches could not be balanced by the mechanism. For example, un upward force large enough could not be balanced by the three constant torque lower winches.

5. Bibliography

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