Increase of Position Accuracy for Cable-Driven Parallel Robots Using a Model for Elongation of Plastic Fiber Ropes

Valentin Schmidt and Andreas Pott

Abstract This paper investigates the modeling of elongation in plastic fiber ropes for cable-driven parallel robots. The aim is to increase the accuracy of such a machine by incorporating a simple model for cable elongation when a force is applied. Several other modeling techniques already exist which take into account pulleys, cable mass, and the cables' Young's modulus. Their calculation is involved and accuracy improvements are yet to be verified completely. Here, a simpler model which only takes into account a theoretical force, based on robot geometry, at a given pose and measured elongation coefficients is proposed. It is implemented and verified experimentally, on the fully constrained IPAnema 3 prototype. It is shown to give an accuracy improvement of two fifths, from 46.5 mm to 29.0 mm average position deviation.

Keywords Cable-driven parallel robot · Accuracy · Modeling · Real-time computation · Elongation

1 Introduction

High speed, acceleration, and a large workspace are properties often associated with Cable-Driven Parallel Robots, from here on referred to as CDPRs. The first such CDPR was designed in the end of the twentieth century [3]. Many active investigations have taken place on this type of robot since then. Commercial prototypes to move a camera for filming live events [1], positioning receivers of giant telescopes [7], and artistic presentations [20] are examples of built or intended cable robot projects. Many more CDPRs prototypes exist for research purposes. These demonstrate inspection and handling solutions to solve automation challenges. While high

V. Schmidt (✉) · A. Pott
Fraunhofer IPA, Stuttgart, Germany
e-mail: Valentin.Schmidt@ipa.fraunhofer.de

A. Pott
e-mail: Andreas.Pott@ipa.fraunhofer.de

P. Wenger and P. Flores (eds.), *New Trends in Mechanism and Machine Science*, Mechanisms and Machine Science 43, DOI 10.1007/978-3-319-44156-6_34

accelerations [8] and large workspaces are verified, the accuracy of such systems is not as high as that of an industrial robot.

CDPR technology has benefited from increased computational power, which is capable of computing the complex underlying kinematics. The forward kinematics in the general case is a mathematically involved problem, having multiple solution sets. This results in many different solving techniques including interval arithmetic [10]. Many specific geometrical cases are still not yet solved [11]. The development of real-time capable algorithms is still an active area of research.

Further models have also been developed, which take into account factors such as pulleys [5], cable mass and elongation [17], or further geometrical properties [13]. Additionally, ovalisation has been shown to cause highly force dependent transmission ratio of winches [19]. These models should bring an increased accuracy to robot prototypes. However, physical verifications through measurements have so far only been shown for the pulley mechanism [18], and have shown only marginal improvement. The geometrico-static [4] or kinetostatic models [6] are probably the most comprehensive so far. However, the computation is even more complex than the standard model and may not be fit for real-time controllers. Especially for plastic fiber cables, the elasticity is one of the biggest contributing factors for a lack in accuracy. Thus, a simple model focusing on this effect is explored here.

In this paper, a simple model to correct for the elongation of plastic fiber ropes is introduced and the improvements on accuracy are examined. This simple model does not even rely on the cable force to be measured, but estimates this from the pose. Good accuracy improvements indicate, that in some prototypes it might be prudent to neglect complicated factors which have almost negligible influences in order to achieve reliable control to gain the best accuracy increase. How well this improvement works on other prototypes still needs to be tested as ranking of accuracy influencing factors is very dependent on prototype specific characteristics. Steel cables for example are not expected to have the same elongation and therefore may not show the same improvement in accuracy.

2 Robot Model

The well known closure constraints to describe the cable lengths l_i of a CDPR are

$$\|\mathbf{a}_i - \mathbf{r} - \mathbf{R}\mathbf{b}_i\|_2 = l_i, \quad \text{for } i = 1, ..., m. \tag{1}$$

where vectors $\mathbf{a}_i$ and $\mathbf{b}_i$ describe the geometry of the fixed frame and mobile platform respectively for each cable i of m total cables. Vector $\mathbf{r}$ and rotation matrix $\mathbf{R}$ describe the platform pose. The influence of pulleys simply adds cable length resting on the pulley defined through radius r_p and angle θ_i in

$$l_i = \theta_i r_p + l_{fi}. \tag{2}$$

The length l_{fi} is not identical as described by vectors in (1), but it is still obtainable through a closed form solution as described in [15, 18].

This forms the basis of a real-time capable inverse kinematics commonly used in cable robot prototypes

$$\mathbf{l} = \varphi^{\mathrm{IK}}(\mathbf{r}, \mathbf{R}), \text{where} \quad \mathbf{l} = \left[l_1, ..., l_m\right]^{\mathrm{T}}. \tag{3}$$

The forward kinematics φ^{FK} is based on this and often solved iteratively via numerical methods. There exists no closed form solution, and performance of these algorithms is very dependent on the robot geometry. For practical purposes, to solve the kinematics for fully constrained CDPRs, numerical methods are used real-time controllers, the implications of which have been discussed [14].

3 Description of Elongation Phenomenon

Elongation of materials under force is a common engineering concept. In the simplest form, such a stress-strain relationship is described through the material's Young's modulus. Stress and strain curves of materials can be found for many materials, but are not fully developed for the woven cables where the interaction of individual strands makes the behavior very complex. It was further shown, that plastic fiber ropes as used in robots for the experimental evaluation have a considerable hysteresis in elongation under force [12].

The current models for cable elongation include the modeling of cable mass [6, 17]. These essentially map the cable catenary in two dimensions and depend on several cable properties including the cross-sectional area A_0, Young's modulus E, and the specific weight ρ_0. It is evident that this is a model with high complexity. In fact, the inverse kinematics considering these functions can only be solved numerically, making implementation on a real-time system difficult.

Instead, the cable can be modeled as a simple spring. Neglecting the cable mass greatly simplifies the modeling effort. For steel cables, this assumption should be reevaluated as these possess a lower strength to weight ratio. The simplest relationship would be the linear one

$$F_i = k_1 \delta l_i + k_0, \tag{4}$$

where the coefficients k_1 and k_0 are a gradient and offset. Failing this, the plastic fiber cables have been shown to have non-linear behavior which can be approximated through a fourth order polynomial

$$F_i = k_4 \delta l_i^4 + k_3 \delta l_i^3 + k_2 \delta l_i^2 + k_1 \delta l_i + k_0. \tag{5}$$

This is the model used in [9]. Some experiments suggest that the elongation follows an increasing exponential curve. In this case, the polynomial could also be replaced by an exponential function

$$F_i = e^{k_1 \delta l_i} + k_0. \tag{6}$$

Regardless of how the cable is modeled, the above equations allow for easy implementation and approximation, which is relevant for real-time controllers. It is important to note that the coefficients k_i are best obtained experimentally. In fact, one can obtain the coefficients when the cables are already installed in the CDPR. This has the advantage that the coefficients smooth out systematic errors which may occur. These systematic errors can be caused by friction in the pulleys or stiffness in the mechanical components, such as the pulley mounting or the winch itself.

Unfortunately, these models require force values to be obtained for each cable at every pose. One can use force sensors to achieve this, but since any change in cable length further alters the cable force, one will have to implement a very complex feedback controller. This in itself is already a big area of current research. Another option is to approximate force values from the given pose information.

4 Real-Time Implementation

Instead of a physical cable model and live force measurements, this paper proposes a mathematical cable model and model-based force approximation for real-time. Another simplification which is employed in this algorithm is to approximate the cable force instead of relying on sensor values. The calculation of this is done through the structure matrix $\mathbf{A}^{\mathrm{T}}$. It describes the interaction of forces on the platform by considering the cable force vector at that pose $\mathbf{f}_p$, and the corresponding external forces as wrench $\mathbf{w}$ in the relation

$$\mathbf{A}^{\mathrm{T}}\mathbf{f}_p + \mathbf{w} = 0. \tag{7}$$

Using this equation and an approximation of forces at the initial pose $\mathbf{f}_i$ enable us to find an approximation for the forces ($\mathbf{f}_a$) distribution at pose p using the equation

$$\mathbf{f}_a = \mathbf{f}_i - \mathbf{A}^{+\mathrm{T}} \left(\mathbf{w} - \mathbf{A}^{\mathrm{T}}\mathbf{f}_i \right). \tag{8}$$

Here, $\mathbf{A}^{+\mathrm{T}}$ is the generalized pseudo inverse of the structure matrix. The wrench w is considered constant in this case, as the robot is currently operated under low dynamics and has no interaction with the environment. In future implementation, the current wrench can be deduced through the trajectory and expected additional forces (such as the weight of an object handled in a pick and place operation).

This very much resembles the closed form solution for finding a force distribution for a CDPR [16]. Any force distribution algorithm could be used to find $\mathbf{f}_i$, but if force sensors are available, this force distribution can also be measured. Using initial measurements can negate some errors, especially if the force sensors are the same used to determine the factors k_i in the Eqs. (4), (5), or (6).

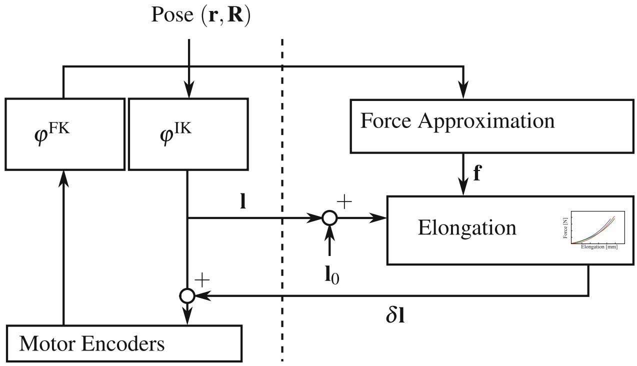

Fig. 1 Simple elongation computation schematic

Of course, this approximation makes some sweeping simplifications to the problem of force distribution. The biggest assumption is that the force distribution at the calibration position $\mathbf{f}_i$ only changes at a given pose due to geometrical factors of that pose. Individual properties of the drive train, including winches and cables are ignored. It should also be mentioned that cable forces can assume values not covered by the closed form method. This is why many more exhaustive algorithms exist [9]. Further, this method assumes that the wrench $\mathbf{w}$ is constant and will not change.

Using the force approximation, any elongation model of the previous section can be used to adjust the cable length by a small difference δl. An algorithm to incorporate in a real-time controller is shown in Fig. 1. The inverse and forward kinematics φ^{IK} and φ^{FK} are calculated as usual, taking into account the pulley mechanism. Elongation is calculated externally potentially even in a separate process. This enables dedicated control, even if the elongation correction should fail, as the kinematics are thoroughly tested and verified.

If the length change δl is also subtracted before being fed into φ^{FK}, then the kinematic codes are completely isolated. Pose values are used to approximate a force and calculate the cable length l. Then, an elongation model from Eqs. (4), (5), or (6) is fed with the values for cable force and cable length. The length includes l_0, which is any free cable length between the winch and the geometrically defining pulley at $\mathbf{a}_i$.

This implementation has several advantages, as it is easy to implement, relatively failsafe and takes into account a prominent factor relevant to plastic fiber ropes. Further, the implementation poses very little additional computational effort for the controller as no numerical methods are needed to solve the presented equations.

5 Accuracy Measurements

Because the proposed model is a big simplification of the actual physical properties for both cables and forces acting on the platform, it should be verified physically. This will aid in understanding which factors are more prominent in the specific prototype and how different accuracy affecting factors could possibly be ranked according to their importance.

Measurements have therefore been conducted on the Fraunhofer IPAnema 3 cable robot. This is a fully constrained robot with eight cables and fibers made of Ultra-High-Molecular-Weight-Polyethylene, which has a better strength to weight ratio than steel but is also much more elastic. The specific rope used is LIROS D-Pro 01505-0600 which has a diameter of 6 mm. Table 1 shows the dimension of the IPAnema 3. It is evident that this is a large CDPR with sidelengths of $16.25 \times 11.30 \times 3.79$ m.

To implement the elongation correction, cable forces were measured using integrated force sensors in the winch. A linear elongation model was used with the measured correction factors being $k_0 = 11382.76$ and $k_1 = 439.13$. These are obtained experimentally using the internal force sensors of one winch and applied for all eight cables.

Measurements of the pose of the CDPR platform were taken via Lasertracker, a measuring device capable of precision of 5 μ m [2]. In successive measurement cycles, each pose was approached at least thirty times. The Euclidean distance to the desired position was measured. Table 2 shows the average distance for each preprogrammed pose. The title "without correction" implies the kinematic algorithm modeling pulleys, and "with elongation correction" for the results for the algorithm introduced here. All except for the two lowest poses, in the z-direction, showed better results.

In summary, it can be said that a simple elongation correction gives an increase in accuracy of almost two fifths. This is a bigger improvement than the modeling of pulleys [18]. Also important to note is that the biggest error observed was in the z-axis. This is due to the very flat geometry of the robot. The flat geometry causes the z-axis to be close to a singularity, with cables pulling almost parallel to this axis. This also explains why a simple elongation correction is very effective in this case. The force difference between the cables will be observed through Eq. (8) and corrected.

Table 1 Geometrical properties of IPAnema 3 CDPR

Cable i	Base vector $\mathbf{a}_1$ [m]	Platform vectors $\mathbf{b}_1$ [m]
1	$[8.18, 5.69, 3.20]^T$	$[0.06, 0.65, -0.26]^T$
2	$[8.22, -5.49, 3.24]^T$	$[0.06, -0.65, -0.26]^T$
3	$[-8.49, -5.32, 3.25]^T$	$[-0.07, -0.65, -0.26]^T$
4	$[-8.54, 5.46, 3.22]^T$	$[-0.07, 0.65, -0.26]^T$
5	$[7.21, 6.46, -0.59]^T$	$[0.10, 0.75, 0.26]^T$
6	$[7.87, -5.56, -0.55]^T$	$[0.10, -0.75, 0.26]^T$
7	$[-8.27, -5.55, -0.53]^T$	$[-0.09, -0.75, 0.26]^T$
8	$[-8.19, 5.65, -0.58]^T$	$[-0.09, 0.75, 0.26]^T$

Table 2 Experimental results (all values in [mm])

	Programmed position (x, y, z)	Accuracy without correction	Accuracy with elongation correction
1	$[0, 0, 1250]$	53.495	34.725
2	$[-110, 110, 1140]$	47.643	17.897
3	$[-110, -110, 1140]$	47.188	17.491
4	$[110, -110, 1360]$	51.568	19.417
5	$[110, 110, 1360]$	52.097	19.715
6	$[-550, 550, 700]$	37.884	23.091
7	$[-550, -550, 700]$	34.233	19.265
8	$[550, -550, 1800]$	57.681	29.468
9	$[550, 550, 1800]$	61.249	32.561
10	$[-880, 880, 370]$	27.907	32.041
11	$[-880, -880, 370]$	20.563	23.727
12	$[880, -880, 2130]$	60.090	37.939
13	$[880, 880, 2130]$	67.394	46.593
14	$[-1100, 1100, 150]$	22.247	28.910
15	$[-1100, -1100, 150]$	12.669	18.210
16	$[1100, -1100, 2350]$	62.892	40.109
17	$[1100, 1100, 2350]$	73.043	51.618
	Average:	46.461	28.987

6 Conclusions

From the results, it can be concluded that the elongation correction is an effective method to increase accuracy for CDPRs with elastic cables. The advantages are that this algorithm can be implemented easily on any controller, and give fast improvements. It may not be applicable to all prototypes as individual factors may be more or less influential depending on their specifics of that CDPR.

Of course, a simple algorithm also ignores several effects. Firstly, the cable forces could be measured instead of approximated. This will invariably bring the issue of force control, but several recent advances may make the increase in accuracy using force control feasible. Further, if one is really dependent on increasing the accuracy significantly, even the elongation correction does not change accuracy parameters by orders of magnitude. The only method to truly achieve the accuracy of industrial robots, a feedback loop with a different pose measurement method must be implemented.

To expand upon this, several approaches can be taken. As mentioned previously, hysteresis is observed in fiber cables. Modeling this would certainly improve the performance of the algorithm, but may also reduce reliability. Improvements of modeling should then also be verified on a CDPR prototype. It is suspected that this is the ovalisation elongation interaction on the winch mechanism which needs to be more deeply understood. As the winch winds cable onto the drum, friction intensifies slowly and if the cable is wound with a high force less cable length is stored. However, if the cable force is released, some elongation on the drum is also reverted. The difficulty is finding a good model to describe this phenomenon. Especially, the interaction between the elongation and the ovalisation have to be further investigated to bring more improvements to CDPR accuracy using fiber cables.

References

1. Cablecam. http://www.cablecam.com
2. Leica absolute tracker asme b89.4.19-2006 specifications (2008)
3. Albus, J.S., Bostelman, R.V., Dagalakis, N.G.: The nist robocrane. J. Res. Natl. Inst. Stand. Technol. **97**(3), 373–385 (1992)
4. Berti, A., Merlet, J.P., Carricato, M.: Solving the direct geometrico-static problem of 3-3 cable-driven parallel robots by interval analysis: Preliminary results. In: Bruckmann, T., Pott, A. (eds.) Cable-Driven Parallel Robots, pp. 251–268 (2013). doi:10.1007/978-3-642-31988-4_16
5. Bruckmann, T.: Auslegung und Betrieb redundanter paralleler Seilroboter. Universität Duisburg-Essen (2010)
6. Gouttefarde, M., Nguyen, D.Q., Baradat, C.: Kinetostatic analysis of cable-driven parallel robots with consideration of sagging and pulleys. In: Advances in Robot Kinematics, pp. 213–221 (2014). doi:10.1007/978-3-319-06698-1_23
7. Hui, L.I.: A giant sagging-cable-driven parallel robot of fast telescope: Its tension-feasible workspace of orientation and orientation planning. In: Taiwan (ed.) Proceedings of the 14th IFToMM World Congress, pp. 373–381. Taipei (2015). doi:10.6567/IFToMM.14TH.WC.OS2.033
8. Kawamura, S., Kino, H., Won, C.: High-speed manipulation by using parallel wire-driven robots. Robotica **18**(1), 13–21 (2000)
9. Kraus, W.: Force control of cable-driven parallel robots. Ph.D. thesis, Universität Stuttgart, Germany (2015)
10. Merlet, J.P.: Solving the forward kinematics of a gough-type parallel manipulator with interval analysis. Int. J. Robot. Res. **23**(3), 221–235 (2004)
11. Merlet, J.P.: Wire-driven parallel robot: Open issues. In: Padois, V., Bidaud, P., Khatib, O. (eds.) Romansy 19—Robot Design, Dynamics and Control, CISM International Centre for Mechanical Sciences, vol. 544, pp. 3–10. Springer, Vienna (2013). doi:10.1007/978-3-7091-1379-0_1
12. Miermeister, P., Kraus, W., Lan, T., Pott, A.: An elastic cable model for cable-driven parallel robots including hysteresis effects. Cable-Driven Parallel Robots (2014)
13. Nguyen, D.Q.: On the study of large-dimension reconfigurable cable-driven parallel robots. Ph.D. thesis, Universite Montpellier, France
14. Pott, A.: An algorithm for real-time forward kinematics of cable-driven parallel robots. In: 12th International Symposium on Advances in Robot Kinematics. Springer-Verlag, Piran Portoroz and Slovenio (2010)
15. Pott, A.: Influence of pulley kinematics on cable-driven parallel robots. In: Latest Advances in Robot Kinematics, pp. 197–204 (2012). doi:10.1007/978-94-007-4620-6_25
16. Pott, A., Bruckmann, T., Mikelsons, L.: Closed-form force distribution for parallel wire robots. In: Computational Kinematics, pp. 25–34. Springer (2009)

17. Riehl, N., Gouttefarde, M., Baradat, C., Pierrot, F.: On the determination of cable characteristics for large dimension cable-driven parallel mechanisms. In: 2010 IEEE International Conference on Robotics and Automation (ICRA), pp. 4709–4714 (2010). doi:10.1109/ROBOT.2010.5509887. http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=5509887
18. Schmidt, V., Pott, A.: Implementing extended kinematics of a cable-driven parallel robot in real-time. In: Bruckmann, T., Pott, A. (eds.) Cable-Driven Parallel Robots, pp. 287–298 (2013). doi:10.1007/978-3-642-31988-4_18
19. Schmidt, V., Pott, A.: Investigating the effect of cable force on winch winding accuracy for cable-driven parallel robots. Proceedings of the Institution of Mechanical Engineers, Part K: Journal of Multi-body Dynamics (2015). doi:10.1177/1464419315586517. http://pik.sagepub.com/content/early/2015/05/20/1464419315586517.abstract
20. Tempel, P., Schnelle, F., Pott, A., Eberhard, P.: Design and programming for cable-driven parallel robots in the german pavilion at the expo 2015. Machines **3**(3), 223–241 (2015). doi:10.3390/machines3030223