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Bending Cycles and Cable Properties of Polymer Fiber Cables for Fully Constrained Cable-Driven Parallel Robots

Valentin Schmidt and Andreas Pott

Abstract In most practical applications for cable-driven parallel robots, cable lifetime is an important issue. While there is extensive knowledge of steel cables in traditional applications such as elevators or cranes, it cannot be easily applied to cable robots. Especially new polymer based materials behave substantially different, but also the conditions for the cable change dramatically. Cable robots have more bending points and a higher variability in cable force and speed than traditional applications. This paper presents a form of bending cycle analysis which can be applied to assess cable wear. This algorithm counts the number of bends per trajectory in each cable segment. The sum gives an indication how much wear a cable receives. Experiments are conducted on a cable robot using different kinds of polymer fibers. The results show that this method is successful in predicting the point at which a cable finally breaks.

1 Introduction

A very important element of cable-driven parallel robots are the cables themselves. The properties of cables, being able to transmit a force over a long distance while remaining flexible, give rise to many of the advantages and disadvantages of cable-driven parallel robots. As a mechanical component, cables (or ropes) have a long history, with the first being made exclusively from biological materials by civilizations several thousand years ago. Today, steel is the dominant material for making cables for a variety of industries. Polymer fibers are finding more applications in recent times, as some show a superior strength to weight ratio and higher flexibility

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[4]. It is expected that their market share increases in the upcoming years, as manufacturers of lifts, cranes, and other hoisting devices make use of these advantages. In all applications, estimating the lifetime of the cables is notoriously difficult and poses a challenge for the adoption of polymer cables. From previous works with steel cables, we know that the lifetime related to several key factors such as bending radius, cable force, and whether it is moving continuously or not. These are summarized in the Freyer Formula which bundles the criteria and vast amounts of historical data to estimate cable lifetimes. But even this knowledge is not easily applicable for cable robots as higher speeds and more complex wear profiles make the application unique. Some recent investigations are looking into these factors such as the abrasive wear [7] or cable fretting [11]. The equivalent does not exist for polymer fibers [10]. There are some recent bending cycle experiments [9], but the amount of data is much less than that for steel cables.

Interestingly, some investigations have been made for deep sea applications [2, 1]. Here, polymer fibers are used extensively in very large mooring applications. As such, wear is investigated extensively including factors such as tension and torsion fatigue [6]. The associated risks and high costs of failure have spurred a lot of research in this application [2].

Even in the case of steel cables, cable-driven parallel robots pose very different stresses and strains on the cables than previous applications. Generally, the number of pulleys is greater, loads are more varying, and directional changes more frequent. This means conventional methods of predicting cable lifetimes (such as the Freyer Formula) have yet to be validated through experiments [10].

In previous works, it is attempted to use bending cycle experiments in order to obtain an estimate for the behavior of polymer fiber ropes. These showed that the lifetime is highly dependent on the cable force, somewhat dependent on the bending diameters, and to some extent also on the cable speed [9]. An expansion on this is to investigate the behavior of polymer fiber ropes in the actual cable robot itself. This includes assessing the bending cycles for a trajectory and monitoring cable lifetime.

This paper tries to give a brief overview of possible polymer fiber materials and their properties, presents a method of analyzing bending cycles for cable robot trajectories, and gives some experimental results to show possible ways of dealing with the cable lifetime issue in the application of cable-driven parallel robots. Breaking strength is still a clear indicator of cable lifetime (when ignoring susceptibility of degradation by ultraviolet light). The breaking strength of the cable provides a basis for sizing cables. Currently, high safety factors (>10) are taken for granted as the lifetime is hard to predict. The experimental results show that the bending cycles are significant in determining cable lifetime. Additionally, monitoring the elastic properties of cables continuously may help in predicting cable rupture. The polymer creep curve can perhaps be monitored to identify a cable near breaking due to its elastic properties [8].

2 Overview of Cables and Cable Robot Properties

In order to explain the motivation and notation conventions used, some preliminaries are introduced here.

A cable-driven parallel robot with four or eight cables indexed by i is primarily defined through vectors which indicate cable attachment points on the moving platform $\mathbf{b}_i$ and the stationary frame $\mathbf{a}_i$. The pose of the platform is defined through a position vector $\mathbf{r}$ and a rotation matrix $\mathbf{R}$. This gives rise to the inverse kinematics where the cable length l of cable i, is determined as

$$l_i = \|\mathbf{a}_i - (\mathbf{r} + \mathbf{b}_i\mathbf{R})\|_2 \quad . \tag{1}$$

Static analysis using this relation is sufficient to determine the necessary control properties. For pulley kinematics, the point $\mathbf{a}_i$ is defined by the cable point entering the last pulley not in the direction of the platform (as this changes with position), but the one in the direction of the winch.

The cable material is not the only property significant to the cables. Major factors of wear include material dependent ones such as UV-radiation and temperature. Further production parameters are also relevant such as the meshing of individual strands, and coating materials. Others factors influenced by the cable robot include the bending cycles and forces applied to the cables. These cause abrasion within the cable as individual strands rub against one another to cause friction. In common bending cycle experiments, the number of successful bending cycles is used as a measure for the lifetime of the cable. Thus, it seems prudent to use a similar approach for cable lifetime within cable-driven parallel robots. To the author's knowledge, there has been no algorithm so far to give the number of bending cycles per rope segment for a given trajectory. Thus, this is presented in the following section. As it is known that cable force is also an important contributing factor, the presented method also provides the ability to take the cable force into account, if it is known.

3 Algorithm for Counting Bending Cycles

As mentioned, bending cycles are an important factor in cable lifetime. However, for cable-driven parallel robots, it is not trivial to assess the bending cycles, as these are not consistent. Other applications such as hoists or cranes have simple one to one relationships between usage cycles and bending cycles.

A single bending cycle is defined by the cable going from a straight position into a bending position or vice versa. Thus, a single pulley actually has two positions where a bending cycle occurs. The first when the rope enters the pulley and is bent around at the pulley radius, and the second when the rope exits the pulley in the other direction. The number of these bends which a cable is subjected to, over a usage period, is a measure of wear. When using a cable robot, not all sections of a cable receive to the same amount of bending cycles. An algorithm (algorithm 1), can be constructed to count these bending positions over a trajectory.

First a parameterization needs to be chosen. In this case, the attachment point $\mathbf{b}_i$ of the cable on the platform is chosen as zero, as is shown in figure 1. The reason for this is that it is consistent for a given robot geometry. When considering a cable robot under external force, it is at least theoretically conceivable that it moves to an infinite position. This means no definite fixed end can be defined on the winch. In this algorithm, cable wear is abstracted into a value representing the number of bending cycles for finite cable segments. The result is a one-dimensional array $\mathbf{v}_i$ in $\mathbb{N}^n$ for each cable i of size

$$n = \frac{l_a}{l_y} \quad , \tag{2}$$

where l_a is the absolute cable length of the entire cable and l_y is the desired segment size to be investigated.

Now we define the bending positions of the cable robot geometry. These are presumed to be static with respect to the $\mathbf{a}_i$ points and the winches which are not expected to move with respect to the robot frame. When the pose of the robot $(\mathbf{r}, \mathbf{R})$ is known, the bending positions can easily be transferred into the cable parameterization. Bending positions are defined by the point $\mathbf{a}_i$, (in the case of pulley kinematics in itself a bending position) in a one-dimensional parameter which refers to cable length. The bending positions are stored in another one-dimenstional array $\mathbf{b}_{pos}$ in $\mathbb{R}^m$ where m is the number of bending positions defined. Figure 2 shows these bending positions for the IPAnema configuration.

In order to determine a correct conversion between the cable parameterization and the bending positions a reference needs to be defined. From this position the length to the first bending position close to $\mathbf{a}_i$ can be determined. For this, a zero or reference position is chosen which is part of many controllers anyway.

For a given trajectory, we can use the inverse kinematics to calculate cable lengths at different points in the trajectory. It is assumed that the points on the trajectory are sufficiently close to one another that the starting length l_s changes linearly to ending length l_e. For each cable, the algorithm then determines which segment has moved across the bending position during this cycle and increments this accordingly. This is shown in algorithm 1.

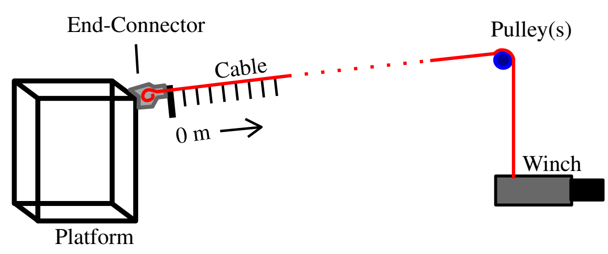

Fig. 1: Cable Parameterization

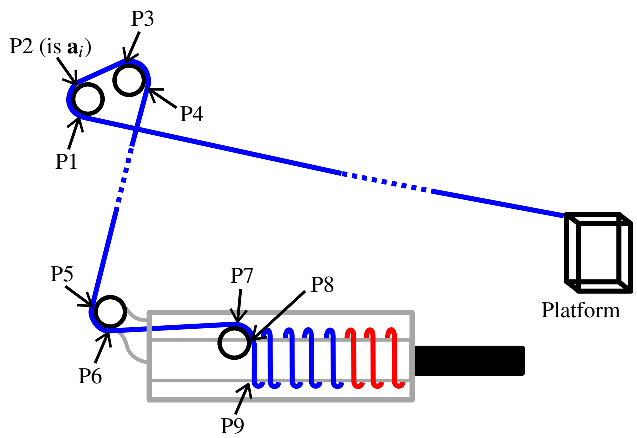

Fig. 2: Bending positions for IPAnema 3 cable-driven parallel robot

Essentially, each of the segments in $\mathbf{v}_i$ which have moved over any of the bending positions in $\mathbf{b}_{pos}$ are incremented regardless of which direction the cable has moved in. It is possible to incorporate other factors such as force, by using a factor f_f proportional to a measured or estimated force. This would turn $\mathbf{v}_i$ into a vector in $\mathbb{R}^n$, but this is an almost trivial change. This was not done in the initial analysis.

The result of this algorithm is shown in figure 3. Here we can see the cable as it is parameterized with zero length at the platform and the associated bending with each segment. Segments with the most wear are those were the number of bending cycles is high.

Algorithm 1 Algorithm for counting the bending cycles during a trajectory

Inputs:
  $\mathbf{v}_i$: to store wear characteristics for cable i
  l_s,l_e: determined by the inverse kinematics
  $\mathbf{b}_{pos}$: bending positions
  l_y: segment size of a single segment
  f_f: optional force factor
Begin:
for every b_{pos} in $\mathbf{b}_{pos}$ **do**
  if $l_s < l_e$ **then**
    $i_{start} \leftarrow \frac{-b_{pos}+l_s}{l_y}$
    $i_{end} \leftarrow \frac{-b_{pos}+l_e}{l_y}$
  else
    $i_{start} \leftarrow \frac{-b_{pos}+l_e}{l_y}$
    $i_{end} \leftarrow \frac{-b_{pos}+l_s}{l_y}$
  for v in $\mathbf{v}[i_{start}, i_{end}]$ **do**
    $v{+}{+}$ **or** $v \leftarrow v + f_f$

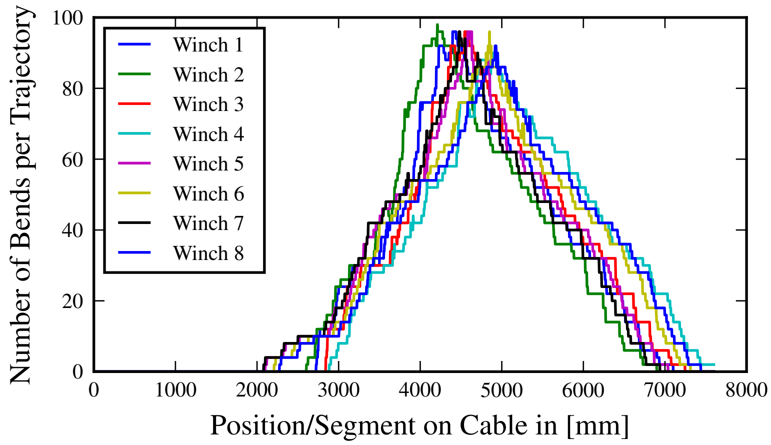

Fig. 3: Bending cycles for an example trajectory on the IPAnema 3

4 Experimental Setup

In order to test the influence of bending cycles, some experiments were performed on a cable robot using polymer fiber cables. The robot in question is the IPAnema 3 cable robot which is part of the IPAnema family of robots developed by the Fraunhofer IPA [5].

The investigations are part of a larger test where materials and other properties are also investigated. The aim was to continuously actuate the cable robot until cable rupture. This gives an insight into the bending cycle analysis. The robot had dimensions of $16.25 \times 11.30 \times 3.79$ m and a cable force range of 10 N to 3 kN. In this experiment, several cables with diameter 2.5 mm were used. The cable materials used in this experiment are outlined in table 1.

Table 1: Cable materials used in the experimental evaluation

Material	Shorthand (Brand)	Weight [g/100m]	Breaking Strength [N]
Ultra High Molecular Weight Polyethylene	Dyneema SK78 ®	336	4070
Aramid (Tejin)	Twaron ®	355	3090
Aramid (DuPont)	Kevlar ®	309	3150
Aramid (Tejin)	Technora ®	304	3400
Thermotropic Liquid Crystalline Polymer	Vectran ®	302	3220
Polybenzobisoxazole	Zylon ®	318	5450

It can be seen that the cable breaking strength is very close to the maximum of the robot capabilities. Usually a much higher factor (often around 10) is used to ensure that the cables do not rupture. In this case, the cable force was chosen to be particularly high in order to ensure that the cables rupture quickly to shorten the overall experiment time. Even with this specification, the trials were conducted over a period of several weeks.

In an endless loop, the cable robot drove the specified trajectory shown in figure 4. The trajectory was chosen to have the similar wear in all cables. Unfortunately, the cable force is highly dependent on the pose of the platform and cannot be maintained in the same manner. However, force levels were ensured to be consistent using a cable force control algorithm [3]. Once a cable breaks, the breaking point is recorded and compared with the theoretical rupture zone.

The experiment was divided into three tests, the first and third at a trajectory speed of 10.000 mm/min while the second was conducted at a trajectory speed of 20.000 mm/min. The distribution of cables is shown in table 2. The cable numbers indicate in which experiment and which winch position each cable has on the frame as it is shown in figure 4. As the force was considerably different between four cables attached at the top frame (1 to 4), and the four cables arranged at the bottom of the frame (5 to 8), these are also given in the table. While the cable forces vary around ten percent for each cable, the force along the entire trajectory is very consistent at each repetition and have an almost identical force profile.

Using force sensors in the winch, a cable rupture can be detected by the sudden loss in cable force. The robot then can be paused and the ruptured cable replaced.

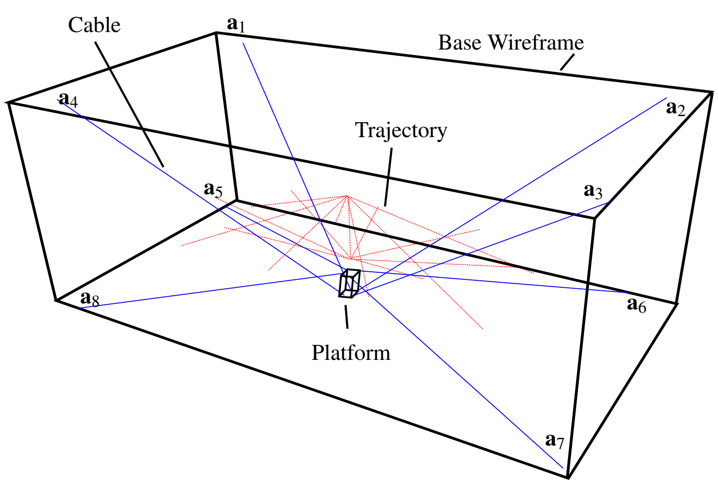

Fig. 4: Test trajectory (red) for polymer cables (blue) in IPAnema 3 geometry (black wireframe)

Table 2: Test distribution per winch for three tests

Test One			Test Two			Test Three		
C-Nr.	Material	Force	C-Nr.	Material	Force	C-Nr.	Material	Force
1.1	Dyneema ®	approx.	2.1	Kevlar ®	approx.	3.1	Dyneema ®	approx.
1.2	Technora ®	270 N	2.2	Twaron ®	270 N	3.2	Technora ®	400 N
1.3	Dyneema ®		2.3	Technora ®		3.3	Dyneema ®	
1.4	Technora ®		2.4	Zylon ®		3.4	Technora ®	
1.5	Vectran ®	approx.	2.5	Kevlar ®	approx.	3.5	Vectran ®	approx.
1.6	Zylon ®	500 N	2.6	Twaron ®	500 N	3.6	Zylon ®	600 N
1.7	Vectran ®		2.7	Technora ®		3.7	Vectran ®	
1.8	Zylon ®		2.8	Zylon ®		3.8	Zylon ®	

5 Experimental Results

The results of the experiment discussed in the previous section show that the bending cycle analysis closely predicts the rupture point of the cable. Table 3 shows the sixteen ruptures experienced across the three tests. The cables lasted around 500 to almost 2000 trajectory cycles, which equates to about 50,000 and 200,000 bending cycles.

Many of the ruptures occurred very close to the theoretically predicted rupture zone. The theoretical rupture zone is sometimes a range and sometimes a specific point because the bending cycle analysis indicated a defined peak of maximum wear, and sometime a wider range of segments with maximum but equally exposed to wear. This is independent of the cable material speed or force applied. There are some four outliers were the rupture position is far away (>10%) from the theoretical rupture zone. Generally, this means that the cable bending is a predominant factor even for polymer fibers.

There is an inherent difficulty when measuring the rupture position. Figure 5 shows a typical cable broken under continuous bending cycles. The breaking zone is defined as the zone where the rupture cable is loosing width on either side, as several individual strands are broken. The measurement of the rupture position was

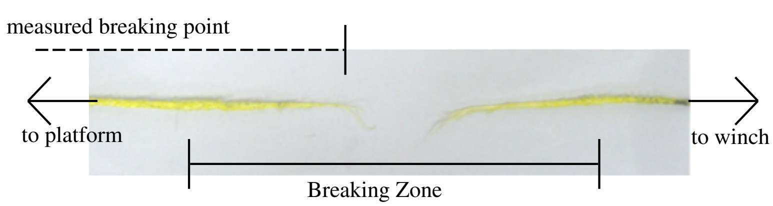

Fig. 5: Determining the breaking position on a cable

done as indicated with distance from the winch. Since polymer fibre cables have more elasticity, the breaking zone is probably more pronounced than for a steel cable. The breaking zone due to bending fatigue is expected to be smaller for steel cables.

For two of the four aforementioned outliers, the cable breaking zone was very large as several very thin strands extended, both on the cable portion leading to the winch and the portion leading to the platform.

Two other conclusions can be drawn from the experiences of driving the cable robot up until cable failure. Firstly, as the cable rupture occurs on the most bent segments of the rope, it will usually occur within or near the winch. This is true for the IPAnema winch, which has five bending positions (as seen in figure 2). For the operation of cable-driven parallel robots, this is positive because a cable does rarely shoot out and becomes a potential harm as it whips across the workspace. Most of the time, the cable remained stuck somewhere in the chain of pulleys. This means that it is harder to replace once ruptured. Secondly, the redundancy in cables in the eight cable robot ensured that the platform remained fairly close to the pose where the cable ruptured along the trajectory. The platform will move to a configuration within the seven actuators robot that remain when one cable is ruptured. At no point during the experimentation did the platform fall to the ground or deviate by more than a couple of centimeters from the trajectory. This also have positive implications on the safety of operation. Of course, it should be noted that the trajectory remained at the center of the workspace.

Table 3: Cable rupture position

Rupture Nr.	Cable Nr.	Rupture Pos. [m]	Theoretical Rupture Zone [m]	Deviation [%]	Bending Cycles
1	1.5	4.40	4.67-4.68	5.8	130
2	1.4	6.87	7.85-7.90	12.5	573
3	1.4	6.12	7.85-7.90	22.0	1009
4	2.6	3.88	4.36	11.0	2098
5	2.5	4.20	4.67-4.68	10.1	2149
6	2.2	7.27	8.03	9.5	2183
7	3.6	9.54	9.58	0.42	138
8	3.6	9.86	9.58	2.92	420
9	3.7	10.30	10.45-10.47	1.53	181
10	3.7	9.64	10.45-10.47	7.84	443
11	3.3	14.16	14.99	5.54	573
12	3.6	9.42	9.58	1.67	163
13	3.8	10.49	10.68-10.70	1.87	565
14	3.7	10.28	10.45-10.47	1.63	97
15	3.6	9.88	9.58	3.13	1185
16	3.7	10.48	10.45-10.47	0.19	1178

6 Conclusion

The lifetime of polymer fiber cables in the use of cable robots is still a very open issue. It was shown that previous knowledge on the significant factors gives an indication of how long a typical cable may last. However, many more investigations need to be done to complete this knowledge. Part of the difficulty is the amount of variation in polymer fiber cables. There are not only very many materials, but the material properties show large variations, even for a single material.

A bending cycle analysis was introduced in this paper. This is easy to implement and can be applied to any cable robot in the current form. It can even be applied to a controller and additionally monitoring cable forces. This should give a very accurate indication of which segment of the rope has endured the most wear. It is expected that this analysis can be applied for steel cables, but a smaller bending zone is expected due to less elasticity.

Experimental results show that the rupture zone in an example cable robot coincides closely with that predicted by the bending cycle analysis. The implication is that bending during use is one of the major contributors to cable wear during the operation in cable robots.

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