Accuracy Improvement for CDPRs Based on Direct Cable Length Measurement Sensors

Christoph Martin[1], Marc Fabritius[1], Johannes T. Stoll[1], and Andreas Pott[2]

[1] Fraunhofer Institute for Manufacturing Engineering and Automation IPA
Robot and Assistive Systems Department
70569 Stuttgart, Germany
christoph.martin@ipa.fraunhofer.de
[2] Institute for Control Engineering of Machine Tools and Manufacturing Units (ISW)
University of Stuttgart
70049 Stuttgart, Germany

Abstract. In many applications of cable-driven parallel robots (CDPRs), accuracy is an important requirement. The accuracy of CDPRs with a controller based only on the standard kinematic model is limited because of effects like cable elongation. Carrying payload on the platform, i.e. applying an external wrench, increases the influence of this effect. To address this problem, we present a cable length correction method based on direct cable length measurement sensors (DCLM-Sensors). With this method, effects like cable elongation can be compensated. In experiments, the position accuracy of the cable robot IPAnema 3 could be improved by 61.49 % without additional payload, and 86.31% with additional payload. We present the integration of the sensor feedback in the cable robot controller and the results of an experimental evaluation on the cable robot IPAnema 3.

Keywords: cable-driven parallel robot, CDPR, direct cable length measurement, DCLM-Sensor, laser sensor, accuracy, elongation, creep

1 Introduction

Cable-driven parallel robots (CDPRs) are a class of parallel robots which use cables to manipulate a mobile platform relative to a fixed frame. The use of cables brings several advantages, such as a large workspace, scalability, a good payload-to-weight ratio, and high dynamics.
Many applications of CDPRs that exploit these properties like 3D-printing or pick-and-place also require a high robot accuracy. Satisfying this requirement can be critical for the suitability of CDPRs [1]. Therefore, improving the accuracy of CDPRs is an important and active field of CDPR research [7, 16]. The accuracy of CDPRs is influenced by various factors such as:

- The CDPR model of the controller and the effects which it considers or neglects (e.g. cable elasticity, cable sagging due to the cable's weight, pulley kinematic)

- The accuracy of the calibration of the parameters of the CDPR model
- Cable properties (e.g. elasticity, creep, hysteresis, wear)
- The behavior of the cables on the winches (e.g. cable flattening, coiling errors, non-linear cable length-to-drive ratio)
- The mechanical properties of the remaining CDPR components: frame, platform, pulleys, drive trains (e.g. manufacturing accuracy, mechanical play, compliance, friction)

A more detailed list can be found in [14, page 26 ff].
Many CDPR controllers in practice are based on simple CDPR models which are able to run in real-time and only require few parameters to be calibrated. They move the platform by translating a desired platform pose to cable lengths through an inverse kinematic code. These lengths are then set with the motor encoders in the winches. A common assumption is that the cable lengths are a linear function of the encoder values. For CDPRs that use coiling winches like the IPAnema [12] or CoGiRo [4], the encoders measure the revolutions of the winch drums. In CDPRs with linear actuators like the MARIONET-VR [7] or IPAnema 2 planar [10, page 357], the encoders measure the linear displacement. Such CDPR controllers neglect the effects listed above. Among these effects, the elongation of the cables due to elasticity plays a major role for the accuracy of CDPRs, especially for CDPRs with plastic fiber cables [16].
In the literature, the following approaches can be found to combat the negative impact of cable elongation. The issue of cable creep which changes the relationship between home pose and cable lengths over time can be mitigated through frequent recalibration of the home pose. Calibration methods for CDPRs can be found in [13] and an automated one in [8]. Both methods take measurements at different poses in the workspace, which may not be possible depending on the application. Sandretto et al. use measurements from a laser tracker [13], while Miermeister uses the internal position and cable force sensors [8]. Another approach is to use a more complex cable model that can account for creep [9]. The application of such models is often hindered by their dependency on parameters that are difficult to measure and may change due to environmental influences.
Focussing on elasticity, in [16], a simple elongation model is used to increase the accuracy of CDPRs. This results in a decrease of the average positioning error by almost 40 %. Hereby, it is assumed that the external wrench acting on the platform is known and constant. Any deviation in this parameter, such as payload, decreases the accuracy of this approach.
Another possibility is to employ feedback control using external sensors. In [1], multiple cameras are used to determine the pose of the platform and the cable directions at the pulleys. This requires that their view on the platform must not be obstructed. Fortin-Côté et al. use additional information from angular sensors measuring the angle of the cables at the pulleys of a suspended cable robot with two cables to increase the accuracy in [3]. Merlet proposes two approaches to directly measure the cable length in [6, 7]. Both are using markers attached to the cable in known intervals. Measuring the actual distance between the markers, the current cable length can be determined. In [7], the idea is to use small strips

of magnetic tape or colored markers which can be detected by a hall sensor or IR optical sensor, respectively. In [6], the method based on colored markers is further investigated. The resolution of this setup depends on the distance of the color sensors and markers, the number of the color sensors and the cable length. With this measurement method, a resolution of 0.1 m is achieved for a cable of 60 m length with 84 markers and 15 color sensors in the given examples.

This paper presents a new correction method for CDPRs based on direct cable length measurement sensors (DCLM-Sensors) attached to each cable. With this method, it is possible to compensate inaccuracies due to cable creep, elasticity, coiling errors, flattening, and non-linear cable length-to-drive ratio. Errors due to other effects like inaccuracies in the calibrated parameters of the CDPR model remain unaffected.
The mechanical design of the DCLM-Sensors used in this paper is presented in [5]. Furthermore, an experimental evaluation of the DCLM-Sensors, comparing the cable lengths measured with the DCLM-Sensors and the cable lengths set with the motor encoders on the IPAnema 3, can be found in [5].
The structure of this paper is as follows: In Section 2, the standard kinematic model of a CDPR and the kinematic of the DCLM-Sensor is defined. In Section 3, the standard CDPR controller and the implementation of the integration of the DCLM-Sensor feedback are explained. Section 4 presents the results of the experimental evaluation, after which the paper closes with the conclusion.

2 Kinematic

In the following, the standard kinematic model of a CDPR and the kinematic of the DCLM-Sensor are introduced. Vectors and matrices are labeled in bold.

2.1 Standard kinematic model of a CDPR

The standard kinematic model of a CDPR is visualized in Figure 1. Two coordinate systems are used. The global coordinate system $\mathcal{K}_0$ which is fixed to the cable robot frame and the moving coordinate system $\mathcal{K}_\mathtt{P}$ which is attached to the moving platform of the CDPR. The CDPR has m cables. The vectors $\mathbf{a}_i \in \mathrm{SE}_3$, $i \in \{1, ..., m\}$ describe the coordinates of the proximal anchor points A_i with respect to the coordinate system $\mathcal{K}_0$, where the cables are connected to the cable robot frame. The vectors $\mathbf{b}_i \in \mathrm{SE}_3$, $i \in \{1, ..., m\}$ describe the distal anchor points B_i of the cables with respect to the coordinate system $\mathcal{K}_\mathtt{P}$, where the cables are connected to the cable robot platform. The pose of the platform $\mathcal{K}_\mathtt{P}$ with respect to $\mathcal{K}_0$ is described by the position vector $\mathbf{r} \in \mathrm{SE}_3$ and the rotation matrix $\mathbf{R} \in \mathrm{SO}_3$. The cables are assumed to be straight lines. Thus, the vectors $\mathbf{l}_i \in \mathrm{SE}_3$, $i \in \{1, ..., m\}$, describing the cables, are defined as follows:

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

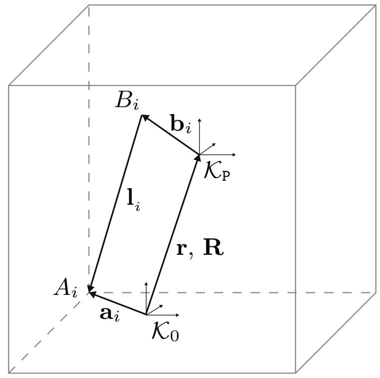

Fig. 1: Kinematic model of a CDPR (modified from [2])

Furthermore, at the proximal anchor points A_i the cables are redirected by pulleys. To take the pulleys into account, the standard kinematic model is developed further in [11]. In this paper, the inverse kinematic (IK) is based on the inverse pulley kinematic model from [11].

2.2 Kinematic of the DCLM-Sensor

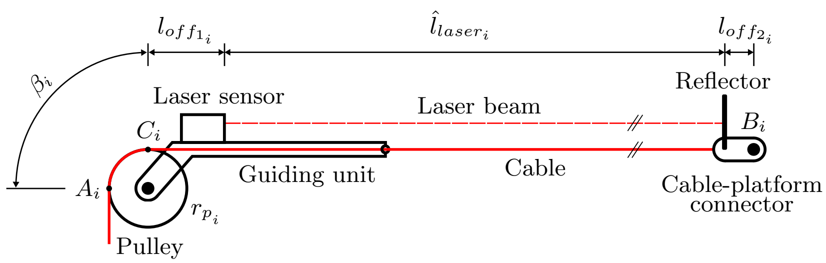

Fig. 2: Schematic sketch of a DCLM-Sensor (modified from [5])

The kinematic of the DCLM-Sensor is explained based on Figure 2. The aim is to determine the cable length from the proximal anchor point A_i to the distal anchor point B_i. The third point C_i is defined as the point where the cable leaves the pulley tangentially. The cable length wound up on the pulley l_{AC_i} is equal to the angle β_i times the pulley radius r_{p_i}. The angle β_i is obtained from the IK and depends on the commanded platform pose. For the straight part of the cable between C_i and B_i, the laser beam is assumed to be aligned parallel to the cable. The straight length is composed of the two offsets $l_{off_{1_i}}$, $l_{off_{2_i}}$ and the measurement of the laser distance sensor $\hat{l}_{laser_i}$. The offsets are set in the home pose as constant values. As a result, we receive the following equation for the cable length $\hat{l}_i$:

$$\hat{l}_i = \beta_i \, r_{p_i} + l_{off_{1_i}} + \hat{l}_{laser_i} + l_{off_{2_i}} \tag{2}$$

3 Implementation

The control scheme of the implementation of the cable length correction controller with the DCLM-Sensors is visualized in Figure 3. The controller is implemented on the IPAnema 3, a redundantly constrained cable robot with eight cables. Each cable of the CDPR is equipped with a DCLM-Sensor. The controller is implemented in TwinCAT 3 from BECKHOFF except for the forward kinematic (FK). The FK is implemented in WiPy [3], an open-source CDPR simulation library developed at Fraunhofer IPA. The algorithm of the FK is based on [15]. It is a proof of concept implementation for static poses to show that the correction method works.

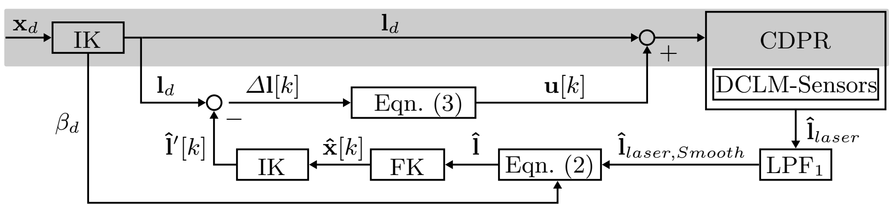

Fig. 3: Control scheme of the DCLM correction controller

3.1 Standard CDPR controller

The standard CDPR controller without any correction is shown in the grey-shaded area in Figure 3 and works as follows:
The commanded desired pose $\mathbf{x}_d$ is given to the IK. The output of the IK, the cable length $\mathbf{l}_d$, is commanded to the drive amplifiers of the CDPR. With the standard controller, there is no feedback whether the real cable lengths and the commanded cable lengths are the same.

3.2 DCLM correction controller

The approach in this paper augments the standard controller with the cable length feedback of the DCLM-Sensors. The controller is developed for the static case, where the pose $\mathbf{x}_d$ does not change. To get the feedback cable lengths from the DCLM-Sensors, the measured lengths of the DCLM-Sensors $\hat{\mathbf{l}}_{laser}$ are

[3] https://gitlab.cc-asp.fraunhofer.de/wek/wirex.git

first filtered with a first-order low pass filter LPF_1 for smoothing. With the filtered measurements $\hat{\mathbf{l}}_{laser,Smooth}$, the cable lengths $\hat{\mathbf{l}}$ are calculated according to Equation (2). The DCLM-Sensor measurements $\hat{\mathbf{l}}_{laser}$ are updated with the laser sensor output rate of 2.5 ms (see Table 2). The values $\hat{\mathbf{l}}_{laser,Smooth}$ and $\hat{\mathbf{l}}$ are calculated each millisecond. The cable length based on the DCLM-Sensor measurements $\hat{\mathbf{l}}$ is given to the FK as an input, which results in the pose $\hat{\mathbf{x}}[k]$. Since the FK is implemented in WiPy, the execution is not real-time capable. Therefore, the index $[k]$ is introduced to denote each execution cycle. With the pose $\hat{\mathbf{x}}[k]$ and the IK, we receive the feedback cable lengths $\hat{\mathbf{l}}'[k]$. To get the control deviations $\Delta\mathbf{l}[k]$, the feedback cable lengths $\hat{\mathbf{l}}'[k]$ are subtracted from the desired cable lengths $\mathbf{l}_d$. The desired cable lengths $\mathbf{l}_d$ and also the angles $\boldsymbol{\beta}_d$ are received from the IK with the commanded desired pose $\mathbf{x}_d$ as input. Since the pose is static, $\mathbf{l}_d$, $\boldsymbol{\beta}_d$, and $\mathbf{x}_d$ do not change. The cable lengths have to be corrected about the cable length deviations $\Delta\mathbf{l}[k]$. Therefore, the deviations are fed to an integration block. The integration block can be described as follows:

$$\begin{aligned} \mathbf{u}[k] &= \mathbf{u}[k-1] + K_I \cdot \Delta\mathbf{l}[k] \\ K_I &= 0.4 \text{ (heuristically chosen value)} \\ k &\text{ ... incremented about 1 each } 1.7 \text{ seconds, WiPy processing time} \end{aligned} \tag{3}$$

If new correction values $\Delta\mathbf{l}[k]$ are available, which means k is incremented by 1, it is multiplied with the factor K_I and smoothly added to the output value of the last cycle $\mathbf{u}[k-1]$ within 1 second. Finally, the output $\mathbf{u}[k]$ of the integration block is added to the cable lengths $\mathbf{l}_d$ to correct the cable length deviations.
In a first approach, the cable length corrections were directly applied to their related cable. By using DCLM-Sensors to measure and control the cable lengths, the cables can be regarded as non-elastic connections. Due to errors in the calibration of the cable robot (positions of A_i and B_i), the mathematical model has errors compared to the real cable robot. Furthermore, there are errors in the measurements of the laser distance sensors. Since the CDPR is redundantly constrained, these errors can lead to set points in the joint space that do not correspond to any platform pose for non-elastic cables. Thus, the first approach could not reach a stationary state. The remedy is to ensure that all points in the joint space correspond to a platform pose. This is done by concatenating an FK and an IK block. The FK is computed by a least-square optimization, which can be interpreted as using pretensioned springs instead of cables minimizing their potential energy [15]. The cable lengths $\hat{\mathbf{l}}'[k]$, which are the output of the IK block, are guaranteed to have a corresponding platform pose under the assumption of non-elastic cables.

4 Experimental evaluation

The DCLM correction controller is evaluated on the cable robot demonstrator IPAnema 3 at the Fraunhofer IPA. Its geometrical parameters are listed in Table 1. As laser distance sensors for the DCLM-Sensors, DL50-P2228 from SICK [4]

[4] https://www.sick.com/de/en/p/p346664 [Accessed: 04-February-2021]

are used. The technical specification of these laser distance sensors can be found in Table 2. Figure 4 shows the overall experimental setup.

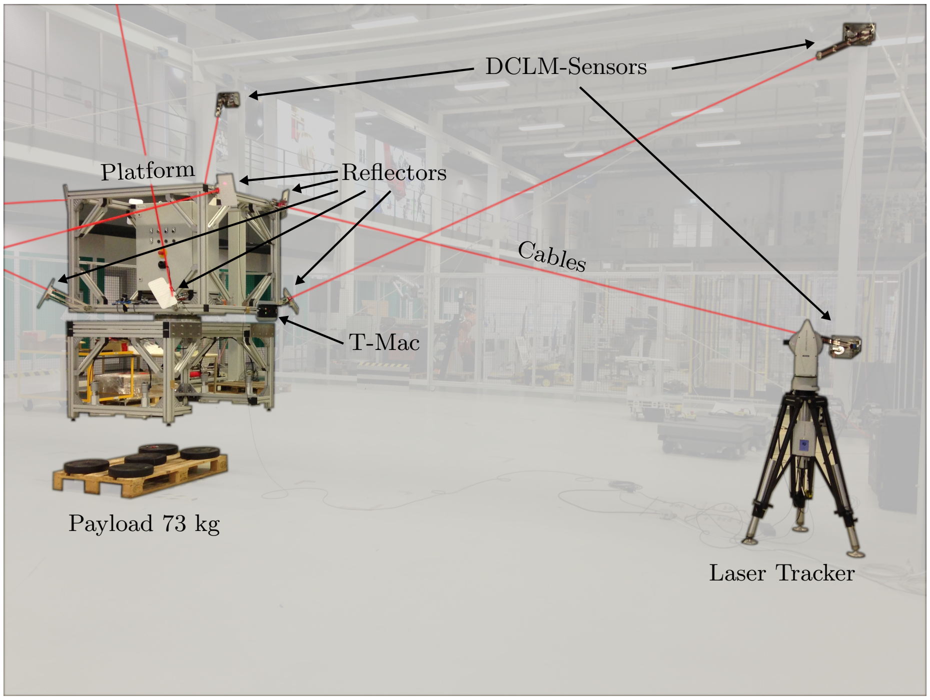

Fig. 4: Experimental evaluation on the IPAnema 3

Table 1: Geometrical parameters of the cable robot IPAnema 3

Cable index i	Proximal anchor points $\mathbf{a}_i$ [m]	Distal anchor points $\mathbf{b}_i$ [m]	Pulley radii r_{p_i} [m]
1	$[7.6029, 5.5952, 3.5665]^\mathsf{T}$	$[0.5488, 0.46, -0.48]^\mathsf{T}$	0.057
2	$[7.5238, -5.5789, 3.5745]^\mathsf{T}$	$[0.5488, -0.46, -0.48]^\mathsf{T}$	0.057
3	$[-7.4614, -5.5621, 3.7536]^\mathsf{T}$	$[-0.5488, -0.46, -0.48]^\mathsf{T}$	0.057
4	$[-7.3114, 5.6113, 3.7408]^\mathsf{T}$	$[-0.5488, 0.46, -0.48]^\mathsf{T}$	0.057
5	$[7.6126, 5.5812, -0.7817]^\mathsf{T}$	$[0.36, 0.7488, 0.48]^\mathsf{T}$	0.057
6	$[7.5427, -5.5851, -0.8525]^\mathsf{T}$	$[0.36, -0.7488, 0.48]^\mathsf{T}$	0.057
7	$[-7.7641, -5.5694, -0.9384]^\mathsf{T}$	$[-0.36, -0.7488, 0.48]^\mathsf{T}$	0.057
8	$[-7.6959, 5.6008, -0.9036]^\mathsf{T}$	$[-0.36, 0.7488, 0.48]^\mathsf{T}$	0.057

Table 2: Technical specification of the SICK laser distance sensor DL50-P2228

Measuring range	200 ... 50 000 mm (with reflector foil)
Typ. repeatability (1 σ)	0.25 mm (moving average set to slow)
Accuracy	Distance $\leq$ 4 m: $\pm$ 5 mm; Distance $>$ 4 m: $\pm$ 3 mm
Output rate	2.5 ms

In the experiments, the accuracy of the cable robot with the standard CDPR controller based on the IK is compared to the accuracy of the DCLM correction controller (see Section 3.2). For the accuracy measurement, the exact pose of the platform of the CDPR is measured with a Leica laser tracker AT960 [5] with a T-Mac attached to the platform. With the T-Mac, all six degrees of freedom can be measured. The measurement accuracy is specified in Table 3.

Table 3: Technical specification of the Leica AT960

Position accuracy	$\pm$ (15 µm + 6 µm / m)
Typical rotation accuracy	$\pm$ 0.01°

For the evaluation of the DCLM correction controller, a grid of 25 static poses with constant orientation of the CDPR-platform in an x-y-plane with a constant z-coordinate (z = 0 m) is chosen. The grid is visualized in Figure 5 with blue dots. The proximal anchor points A_1,...,A_8 of the cable robot are displayed with

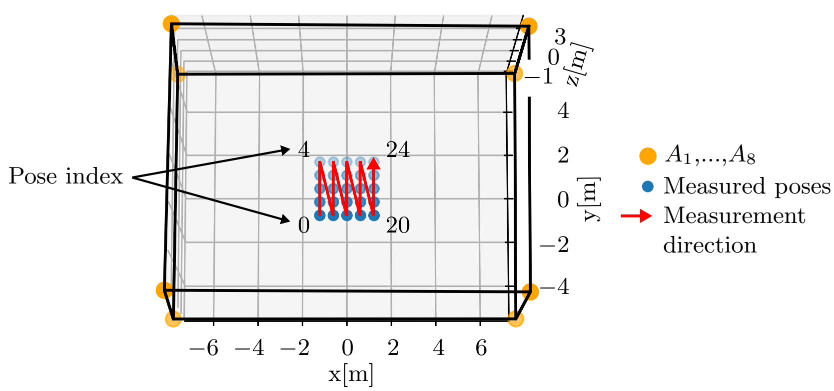

Fig. 5: Measured poses to evaluate the DCLM correction controller [5]

5 https://www.hexagonmi.com/de-de/products/laser-tracker-systems/leica-absolute-tracker-at960 [Accessed: 04-February-2021]

orange dots. The evaluated grid is quite small compared to the cable robot frame but due to the setup of the cable robot with the heavy end-effector the workspace is limited. The grid is evaluated twice in the order following the red arrow. The first time directly after recalibration of the home pose and without payload. The second time, a payload of 73 kg is added. Each run takes around 40 minutes. At each pose, first the accuracy of the IK is measured. Afterwards, the DCLM correction controller is enabled and after a waiting time of 25 seconds to let the controller reach a stationary state, the accuracy of the DCLM correction controller is measured. Each measurement is taken and averaged over one second.

4.1 Accuracy results of the DCLM correction controller

The results of the evaluation are shown in Figure 6 and Figure 7. Heatmaps are chosen to visualize the error. The evaluated poses are marked with black dots, the color is a measure for the error. The relation between color and error value is given by the color bar on the right for each line, respectively. Between the measured poses, bilinear interpolation is chosen. The heatmaps in the left column show the results of the error with the standard controller based on the IK, the ones in the right column the error with the DCLM correction controller. Figure 6a to Figure 6d show the position error, Figure 7a to Figure 7d the orientation error. The displayed position error is calculated by the 2-norm between the commanded position and the measured position with the laser tracker. The orientation error is calculated by the angle of the rotating phasor representation. As can be seen from the graphs, the mean position and orientation accuracy can be significantly improved with the DCLM correction controller. Without payload, the mean position accuracy is improved by 61.49 %, the mean orientation accuracy by 62.5 %. For the experiments with a payload of 73 kg, the position accuracy improvement accounts to 86.31 %, the orientation accuracy increases about 61.9 %. The absolute numbers of the experimental results can be found in Table 4.

Table 4: Results of the experimental evaluation

	Position error [mm]				Orientation error [°]			
	Mean	Min.	Max.	Std. Dev.	Mean	Min.	Max.	Std. Dev.
IK	3.09	1.43	6.57	1.3314	0.16	0.04	0.31	0.0661
DCLM-Sensor	1.19	0.42	2.60	0.6064	0.06	0.02	0.10	0.0217
IK, 73 kg	13.51	8.58	17.00	1.8928	0.21	0.03	0.35	0.0807
DCLM-Sensor, 73 kg	1.85	0.79	3.77	0.7601	0.08	0.04	0.13	0.0250

The orientation improvement of the experiments with payload is in the same magnitude as without payload. Regarding the position accuracy, the improvement for the experiments with payload is much higher compared to the experiments without payload. This is due to the high position deviation of the standard

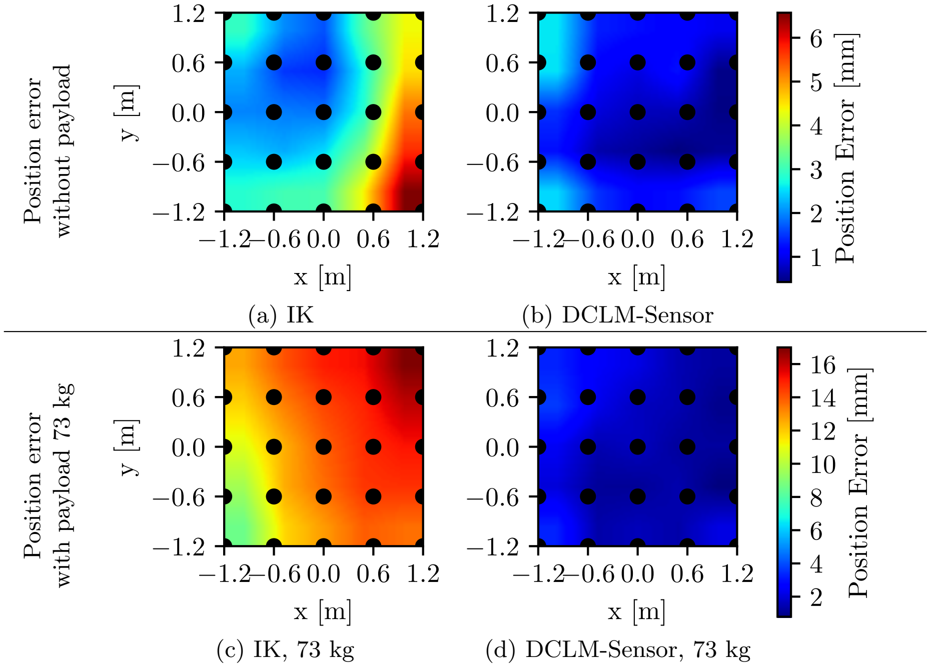

Fig. 6: Position accuracy of IK versus DCLM-Sensor, x-y-plane (z = 0 m)

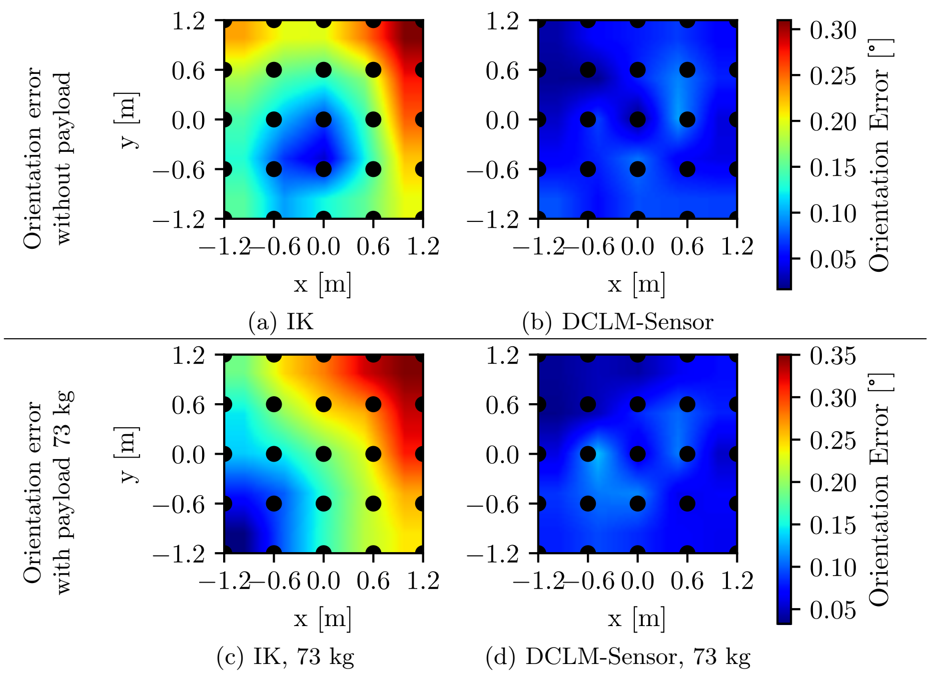

Fig. 7: Orientation accuracy of IK versus DCLM-Sensor, x-y-plane (z = 0 m)

CDPR controller with payload caused by the elasticity of the cables. Comparing the mean position accuracy of the DCLM correction controller with and without payload, the accuracy with payload is about 0.66 mm worse. The assumption for this deterioration is that the cable force distribution changed due to the payload. The level of the forces of the lower cables decreases. Due to cable sagging, the laser does not measure exactly parallel to the cable which leads to cable length measurement errors.
Furthermore, in Figure 6c and Figure 7c the cable creep effect due to the payload can be seen. The accuracy becomes worse the longer the experiment takes. Both effects, elasticity and creep, can be compensated with the DCLM correction controller.

5 Conclusion

In this paper, we present a new cable length correction method based on a laser sensor system for direct cable length measurement to increase the accuracy of CDPRs. Thus, it is possible to compensate effects on the accuracy, such as cable elongation due to elasticity or creep. An experimental comparison of the accuracy between a standard CDPR controller based on the inverse pulley kinematic model [11] and a controller with feedback from DCLM-Sensors shows a significant improvement of the cable robot accuracy.
In future research, we plan to evaluate the direct cable length measurement correction controller with another cable robot platform and thus in a bigger workspace. Also, different orientations are planned to be evaluated. Furthermore, we are working towards a control concept to integrate the feedback of the DCLM-Sensors in a real-time capable way, since the presented controller is not real-time capable. Another possible application of the direct cable length measurement system is the auto calibration of the home pose of CDPRs.

References

[1] Tej Dallej et al. "Modeling and vision-based control of large-dimension cable-driven parallel robots using a multiple-camera setup". In: *Mechatronics* 61 (2019), pp. 20–36.

[2] Marc Fabritius, Christoph Martin, and Andreas Pott. "Calculation of the Collision-Free Printing Workspace for Fully-Constrained Cable-Driven Parallel Robots". In: *ASME 2018 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. American Society of Mechanical Engineers Digital Collection. 2018.

[3] Alexis Fortin-Côté, Philippe Cardou, and Alexandre Campeau-Lecours. "Improving cable driven parallel robot accuracy through angular position sensors". In: *2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE. 2016, pp. 4350–4355.

[4] Johann Lamaury and Marc Gouttefarde. "Control of a Large Redundantly Actuated Cable-Suspended Parallel Robot". In: *2013 IEEE International Conference on Robotics and Automation*. IEEE. 2013, pp. 4659–4664.

[5] Christoph Martin et al. "A Laser-Based Direct Cable Length Measurement Sensor for CDPRs". In: *Robotics* 10.2 (2021). ISSN: 2218-6581. DOI: 10.3390/robotics10020060. URL: https://www.mdpi.com/2218-6581/10/2/60.

[6] Jean-Pierre Merlet. "Improving cable length measurements for large CDPR using the Vernier principle". In: *Cable-Driven Parallel Robots*. Ed. by Pott A. and Bruckmann T. Vol. 74. Springer, 2019, pp. 47–58.

[7] Jean-Pierre Merlet. "MARIONET, A Family of Modular Wire-Driven Parallel Robots". In: *Advances in Robot Kinematics (ARK)*. Springer, 2010, pp. 53–61.

[8] Philipp Miermeister and Andreas Pott. "Auto Calibration Method for Cable-Driven Parallel Robots Using Force Sensors". In: *Latest Advances in Robot Kinematics*. Ed. by Lenarcic J. and Husty M. Springer, 2012, pp. 269–276.

[9] Jinlong Piao et al. "A Polymer Cable Creep Modeling for a Cable-Driven Parallel Robot in a Heavy Payload Application". In: *Cable-Driven Parallel Robots*. Ed. by Gosselin C. et al. Vol. 53. Springer, 2018, pp. 62–72.

[10] Andreas Pott. *Cable-Driven Parallel Robots: Theory and Application*. Vol. 120. Springer, 2018.

[11] Andreas Pott. "Influence of Pulley Kinematics on Cable-Driven Parallel Robots". In: *Latest Advances in Robot Kinematics*. Ed. by Lenarcic J. and Husty M. Springer, 2012, pp. 197–204.

[12] Andreas Pott et al. "IPAnema: A family of Cable-Driven Parallel Robots for Industrial Applications". In: *Cable-Driven Parallel Robots*. Ed. by Bruckmann T. and Pott A. Vol. 12. Springer, 2013, pp. 119–134.

[13] Julien Alexandre Dit Sandretto et al. "Certified Calibration of a Cable-Driven Robot Using Interval Contractor Programming". In: *Computational Kinematics*. Ed. by Thomas F. and Perez Gracia A. Vol. 15. Springer, 2014, pp. 209–217.

[14] Valentin Schmidt. "Modeling Techniques and Reliable Real-Time Implementation of Kinematics for Cable-Driven Parallel Robots using Polymer Fiber Cables". PhD thesis. University of Stuttgart, 2017.

[15] Valentin Schmidt and Andreas Pott. "Implementing extended kinematics of a cable-driven parallel robot in real-time". In: *Cable-driven parallel robots*. Springer, 2013, pp. 287–298.

[16] Valentin Schmidt and Andreas Pott. "Increase of Position Accuracy for Cable-Driven Parallel Robots Using a Model for Elongation of Plastic Fiber Ropes". In: *New trends in mechanism and machine science*. Ed. by Wenger P. and Flores P. Vol. 43. Springer, 2017, pp. 335–343.