A novel winch system for a precise cable length control of a cable-driven parallel robot system

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Abstract

A cable-driven parallel robot (CDPR) is a special class of parallel robots in which rigid legs are replaced by flexible cables. The cables connect the end-effector to the winches which manipulate the end-effector pose by changing the cable length. The position accuracy is an important design parameter when developing CDPR. The winch is a very important part of a CDPR, and its accuracy has a large effect on the CDPR accuracy. This winch design enables precise control of cable length because there is no position error introduced by the winch configuration and no reduction of available cable length. To validate the accurate control of the cable length by the new winch design, an experiment of writing ISR on a vertical wall was conducted. The writing test was successfully performed which demonstrated the accurate control of the cable length by the winch without using any complex equations.

1 Introduction

A cable-driven parallel robot (CDPR) is a special class of parallel robots in which the rigid legs are replaced by flexible cables. As shown in figure 1 a CDPR is a parallel kinematic machine mainly consisting of an end-effector(EE), cables, winches, pulleys and rigid frame [1-2]. The cables connect the end-effector to the winches which manipulate the end-effector pose by changing the cable length.
With the increasing research on CDPR, and an ever increasing number of prototypes [3,10,11,12], the CDPR is known to be energy efficient due to the low moving mass. The first system to pursue an industrial application was the NIST Robocrane in 1989[4]. Later more thorough theories for classification, kinematics, and statics were developed [5]. Due to the advantages of cable robot system, such as its high acceleration motion, high payload manipulation and large workspace, various applications have been exploited. The ultrahigh speed FLACON [6] has been proposed and the high payload CDPR, MARIONET-CRANE [7], is developed that can lift up to 2 tons in most workspace. The largest application for a CDPR is the Five hundred meter Aperture Spherical radius Telescope (FAST) [8] that has been built in southwest China.
We may also distinguish the types of CDPR according to the number of cables, such as fully-constrained and under-constrained. Fully-constrained CDPR [9] has the number of cable that must be at least n+1 (n is number of degree). Under-constrained CDPR [9] is with at most n cables for n DOF motion. In this paper we will focus on the case of the fully-constrained CDPR.
Although there are many advantages of using cable array robots, several critical issues relating to their design and use must be addressed. Some of these issues include complexities in the kinematic description of the robot, the advantages and disadvantages of using redundant cables and cable flexibility.

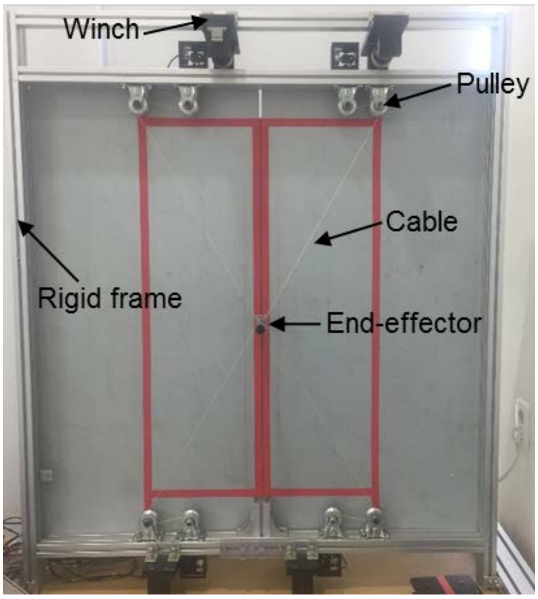

Figure 1 Core elements of a CDPR

The position accuracy is one of the important design parameters when developing CDPR. The winch is an essential part of a CDPR, and its accuracy has a significant effect on the CDPR accuracy. The winch includes many components which enable the change in cable length.
In this paper, we proposed a new winch design that the cable can be always released at the same position. This winch design enables precise control of CDPR cable length, because there is no position error introduced by the winch configuration and no reduction of available cable length.

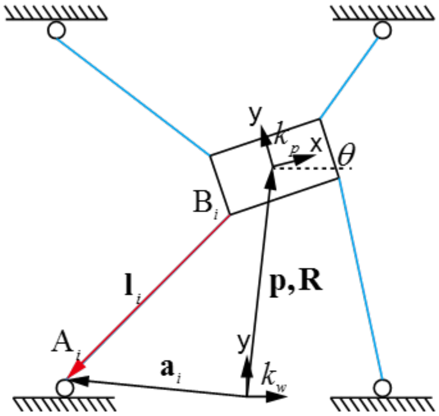

Figure 2 Kinematics structure for a planar CDPR

2 Inverse kinematics of CDPR

The general kinematic structure of the planar CDPR is shown in figure 2. A vector describing *i*-th individual cable is shown using a red solid arrow $\mathbf{l}_i$ (i=1,..,n). The world coordinate system are denoted as k_w and k_p respectively. For the planar cable robot is necessary write a set of kinematic transformations, which calculate the required cable lengths for a given pose, and the pose for given cable lengths.

The pose of the end-effector is defined by its Cartesian position *x*, *y* and orientation *θ* relative to the world coordinate system. Positioning vectors $\mathbf{a}_i$ denote the proximal anchor points on the frame, the vectors $\mathbf{b}_i$ are the relative positions of the distal attachment points on the movable end-effector. Then, given vector $\mathbf{p}$ and rotation matrix $\mathbf{R}$ the closed-form solution for any cable length can be obtained as in (1).

$$\mathbf{a}_i - \mathbf{p} + \mathbf{R}\mathbf{b}_i = \mathbf{l}_i \tag{1}$$

where $\mathbf{p} = \begin{bmatrix} x \\ y \end{bmatrix}$ and $\mathbf{R} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}$.

3 Winch Design

3.1 Drum direct coiling winch

The several prototypes of CDPR have been built in the 90's, among them the famous ROBOCRANE (1992) [4], the FALCON robot (1995) [6] and the rescue robot of Tadokoro (1999) [13], while the principle was partly patented (1996) [14]. All of those CDPR winches were as shown in figure 3, coiling cable with the drum directly linked to the motor.

This type of winch typically allows multi-layer coiling of cable. However, coiling a cable in multi-layer can introduce problems of damaging cables or inaccurate cable coiling. The upper layers have a tendency to crush the lower layers, while the lower layers have a tendency to pinch upper layers. Also, the cable can overlap in the same place, which causes the different coiling radius and produces cable length errors compared to the desired cable length.

3.2 Fleet angle type winch

In order to address the above problems, in the 2000's further prototypes have been developed such as the SEGESTA robot (Hiller et al., 2005)[15] and other prototypes by Barrette and Gosselin (2005)[16], Fattah and Agrawal (2005)[17]. They proposed fleet angle type winch as shown in figure 4.

The fleet angle based on hoisting drum design [18] is the angle created at the point of intersection of a line drawn from the inside edge of the drum flange and along the center line of the cable lead, and a line drawn from the center of the drum at right angle to it. When a cable leads to a leading pulley and on to a drum, the cable will not

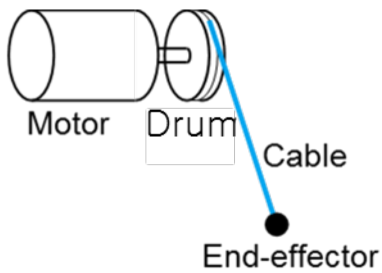

Figure 3 The concept of a drum direct coiling winch

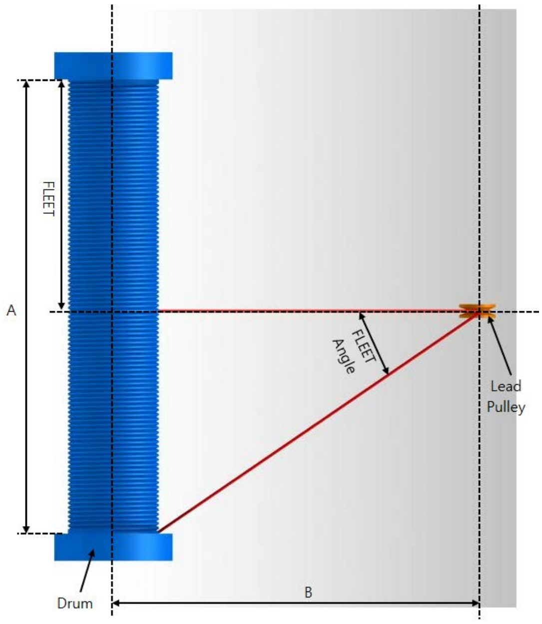

Figure 4 Fleet angle type winch

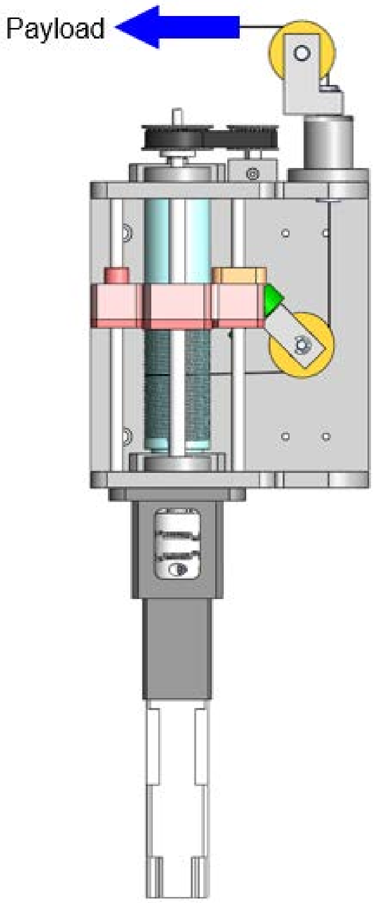

Figure 5 Design of a pulley guiding winch

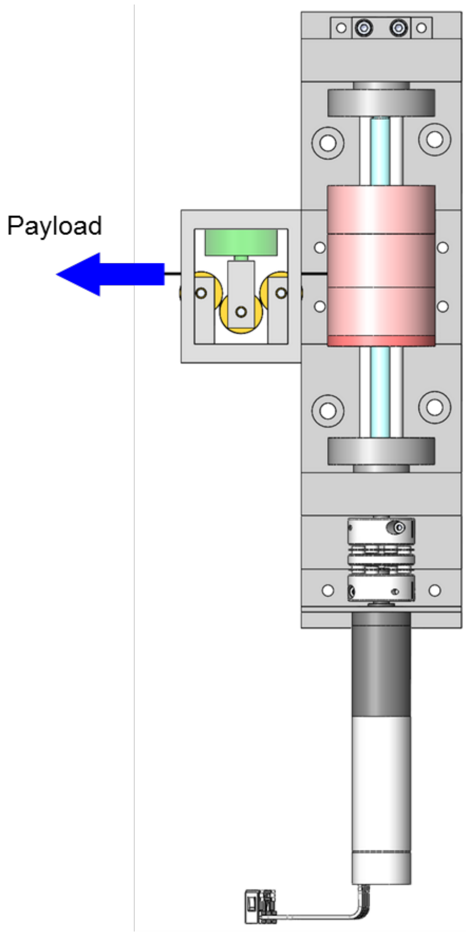

Figure 6 Design of a drum sliding winch

remain in good alignment with the pulley but will deviate to either side depending on the width of the drum and the distance from the lead pulley.
As shown in figure 5, the cable length between the pulley and drum can be changed according to the position of the lead pulley which can be considered as one of cable connection points on the end-effector of CDPR. The position change should be considered in measurement of cable lengths. The encoders can only measure relative cable lengths and therefore we have to use complex equations to correctly determine the cable length and control the cable length [15].

3.3 Pulley guiding winch

In order to address the problems of the fleet angle type winch, in 2010's IPAnema[5] and INRIA[7] cable robot teams have proposed the guiding pulley winches. As shown in figure 5, this winch design includes a drum to wind a single cable precisely, a guide pulley to uniformly reel the cable and several pulleys to guide the direction of the cable. The motor is connected to an additional gear mechanism that moves a cable guidance in parallel to the drum. Due to the equal pitch of the drum and the spindle, the relative distance between the coiled cables is constant allowing reliable coiling and uncoiling of the cable.

This accurate coiling and uncoiling of the cable is especially important when the velocities and accelerations of the cables are very high for cable robots. The guidance includes a pulley that redirects the cable in parallel to the axis of the motor.
At the end of the guidance, another pulley mechanism allows an omnidirectional redirection of the cable into the inner workspace of the cable robot. However, the size of the guiding pulley can make a certain length of the drum to be unavailable for releasing or coiling a cable to winch drum.

3.4 New design of drum sliding winch

Instead of using a guide pulley that has some inaccurate motion, we made a new design of winch that a rolling ball screw is arranged at the center of the winch. That forces the drum to slide on three eccentric guiding shafts, as shown in figure 6. If the lead width of the rolling ball screw and the pitch of the cable groove of the drum are designed to be the same, the cable can be always released at the same position. This winch design enables precise control of cable length at winch, because there is no position error introduced by the configuration of the winch and no reduction of available cable length.

Figure 7 Winch coiling accuracy experimental set up

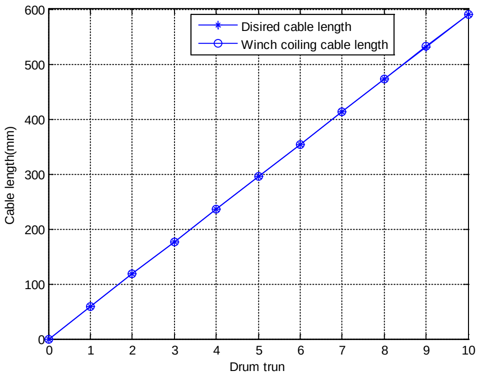

Figure 8 Experimental result of accurate cable length of new drum sliding winch

4 Experimental set up and results

4.1 Experimental set up for winch coiling accuracy

In order to validate the accurate control of cable length by new drum sliding winch, an experimental set up is built as shown in figure 7. The cable moves vertically between the aluminium profiles. The laser distant sensor to measure the end-tip position is fixed at the bottom of the aluminium profile and bearings that allows the laser reflecting steel plate to move smoothly. Winding cable length measured by laser distance sensor is shown in figure 8. The drum turn gives 360° angle command to the motor. The cable length error is less than 1mm for 10 turns.

4.2 CDPR position control for writing ISR

To validate the accurate position control of the planar cable robot by the new drum sliding winch, an experiment of writing ISR on a vertical wall was conducted. The writing test was successfully performed as shown in figure 9

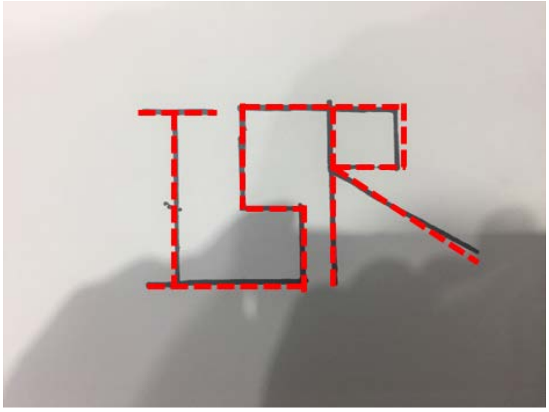

Figure 9 The ISR written by a vertical planar CDPR consisting of the drum sliding winches. (red dashed lines: commanded, black solid lines: written)

which demonstrated the accurate control of the cable lengths by the combination of new drum sliding winches without using any complex equations.

5 Conclusion and future work

In this paper, we proposed a new winch design that the cable can be always released at the same position. This winch design enables precise control of cable length because there is no position error introduced by the configuration and no reduction of available cable length. Also cable length measurement by the laser distance sensor confirmed the accuracy of winch coiling cable length. In the future, we will extend 4 winches system to 8 winches CDPR to build a 3D spatial CDPR. In addition, we will add load cells for the more precise position control of the CDPR.

Acknowledgment

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6 References

[1] XueJun J., Dae I. J., Xuemei J., Sukho P., Jong-Oh P., Seong Y. K. "Workspace Analysis of Upper Limb for a Planar Cable-Driven Parallel Robots toward Upper Limb Rehabilitation," 14th International Conference on Control, Automation and Systems, Korea, 2014, pp. 352-356.

[2] Philipp M., Andreas P., Alexander V., "Dynamic modeling and hardware-in-the-loop simulation for the parallel cable robot IPAnema, " ISR/Robotik 2010, Germany.

[3] Kraus, W., Andreas P., Alexander V., "Investigation on a Planar Cable-Driven Parallel Robot," Proceedings

of ROBOTIK 2012, 7th German Conference on Robotics, Munich, Germany, 2012, pp. 1-6.

[4] J. Albus, R. Bostelman and N. Dagalakis, “The NIST Robocrane,” Journal of Robotic Systems, Vol. 10, No. 5, 1993, pp. 709-724.

[5] Andreas P., Hendrik M., Werner K., Valentin S., Philipp M., and Alexander V., “IPAnema: a family of cable-driven parallel robots for industrial applications,” Cable-Driven Parallel Robots. Springer, 2013, pp. 119-134.

[6] Sadao K., Choe W., Hitoshi K.,Satoshi T., and Ken K., “Development of an Ultrahigh Speed Robot FALCON Using Parallel Wire Drive Systems,” IEEE International conference on Robotics and Automation, 1995, pp. 215-220.

[7] Jean-Pierre M., “MARIONET, A Family of Modular Wire-Driven Parallel Robots,” Lenarčič J, Stanisic MM (eds.) Advances in Robot Kinematics: Motion in Man and Machine, 2010, pp. 53-61.

[8] Hui, L. I., “A Giant Sagging-Cable-Driven Parallel Robot of Fast Telescope: Its Tension-Feasible Workspace of Orientation and Orientation Planning, ” Shuo Hung Chang(Ed.), Proceedings of the 14th IFToMM World Congress, Taipei, 2015, pp. 373-381

[9] Xiumin D., Ou M., and Qi L., “Singularity Analysis of Planar Cable-Driven Parallel Robots,” 2008 IEEE Conference on Robotics, Automation and Mechatronics, China, 2008, pp. 272-277.

[10] Pott, A., Meyer, C., Verl, A., “Large-scale assembly of solar power plants with parallel cable robots.” 41st International Symposium on Robotics (ISR) and 6th German Conference on Robotics (ROBOTIK), 2010, pp. 1-6.

[11] Chablat, D., Ottaviano, E., Moroz, G., “A comparative study of 4-cable planar manipulators based on cylindrical algebraic decomposition,” International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, 2011, pp. 1-10.

[12] C. Antonya, “Force Feedback in String Based Haptic System,” Procedia Computer Science 25, 2013, pp.90-97.

[13] Satoshi T., Richard V., Manfred H., Toshi T., “A portable parallel manipulator for search and rescue at large-scale urban earthquakes and an identification algorithm for the installation in unstructured environments,” International Conference on Intelligent Robots and Systems(IROS), Kyongju, 1999, pp. 1222-1227.

[14] Thompson C.J., Campbell P.D., “Tendon suspended platform robot, ” United States Patent EP0696948 A1, McDonnel Douglas Corporation 1996.

[15] Shiqing F., Daniel F., Marc T., Frank B., and Manfred H., “Motion Control of a Tendon-Based Parallel Manipulator Using Optimal Tension Distribution,” IEEE/ASME TRANSACTIONS ON MECHATRONICS, Vol. 9(3), 2004, pp. 561-568.

[16] Barrette G., Gosselin C., “Determination of dynamic workspace of cable- driven planar parallel mechanisms, ” ASME Journal of Mechanical Design, Vol. 127(2), 2005, pp. 242-248.

[17] Fattah A., Agrawal S.K., “On the design of cable-suspended planar parallel robots, ” ASME Journal of Mechanical Design, Vol. 127(5), 2005, pp. 1021-1028.

[18] Dubbel: Handbook for mechanical engineering, 19.Edition, ISBN 978-3-642-17305-9.

7月7日（星期五）Friday , July 7, 2017 , Room: M3-04

主题/Topic		设计方法学 Design Methodology
会议室/Room 1		M3-04
Time	Number	Paper Title
09:30-09:50	No.83	一种用于电缆驱动并联机器人系统的精确电缆长度控制的新型绞盘系统 A Novel Winch System for a Precise Cable Length Control of a Cable-driven Parallel Robot System
		XueJun Jin
		School of Mechanical Engineering, Chonnam National University, Gwangju, Korea Medical Microrobot Center, Robot Research Initiative, Chonnam National University, Gwangju, Korea
09:50-10:10	No.21	基于.net Framework C#的控制软件编程平台的设计 The design of automation software development platform based-on .net Framework C#
		马立新，王伟　Jack Ma, Harris Wang
		Automation Platform, CODESYS (China), China
10:10-10:30	No.86	A 3D Shape Tracking Algorithm for Flexible Needle in Brain Surgery
		PhuBao Nguyen
		School of Mechanical Engineering, Chonnam National University, Gwangju, Korea Medical Microrobot Center, Robot Research Initiative, Chonnam National University, Gwangju, Korea
10:30-10:40	海报 Poster session & Tea break	
10:40-11:20	Keynote Speech	从全球商业趋势到机器人市场，产品和核心技术 From Global Business Trends to Robotics Markets, Products and Core Technology
		Prof. Andrew A. Goldenberg
		Chief Technology Officer SkyNet Group Limited, Hong Kong President & Founder of ESI, Canada Professor Emeritus, University of Toronto, Canada
11:20-12:00	Keynote Speech	人工智能与机器人：过去、现在与未来 AI and AI robot: Past, Now and Future
		Prof. Il Hong Suh
		Professor of Hanyang University General Chair of IROS 2016, Korea
12:00-12:50		午餐 Lunch Break

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