A Novel Actuation Mechanism for High-Bandwidth Bidirectional Rotation of Cable-Driven Revolute Joints

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Abstract. In recent years, cable-driven revolute joints have been successfully applied in various robotic fields. However, two major concerns remain unsolved. (i) The pull-only characteristic of cable requires additional actuators or a passive low-bandwidth resetting mechanism for bidirectional rotation. (ii) The actuation performance is constrained by the nonlinear relationship between the rotations of the revolute joint and the motor. This paper proposes a general actuation mechanism for a large group of cable-driven revolute joints of various shapes and sizes. A pulley with two separate non-circular tracks, which can retract and release two-side cables simultaneously and independently, is designed to achieve high-bandwidth bidirectional rotation with only one motor while creating a linear relationship between the joint and motor rotations. The profile of the pulley track is depicted with differential equations and the calculation process facilitates revolute joints of various symmetric or asymmetric configurations. The design is verified by the simulation with a numerical example of real-world parameters. Results show the advantages of the proposed mechanism in contrast with the conventional pulley with a circular track profile on both concerns. This mechanism can potentially enlarge the application of cable-driven revolute joints with space and payload limitations, in addition to the requirements of highly dynamic performance.

Keywords: cable-driven · revolute joint · bidirectional actuation · linear motion transmission

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1 Introduction

Actuating a revolute joint by cables is advantageous in that it avoids the weight and volume required to house a motor that directly connects to the joint or a linkage structure that transmits the output of a motor placed elsewhere. Therefore, cable-driven mechanisms are especially popular, and sometimes are even the only option to design compact and delicate hardware devices, such as robotic hands [3,11], robotic tails [10,16], surgical tools [5,8], parallel platforms [19,23], lightweight manipulators [7,22], *etc.*

However, it has been proved that at least $n + 1$ active cables are required to fully actuate a mechanism with n Degrees of Freedom (DoFs) [13], as cables can only provide pulling forces. Driving each active cable independently [3,14, 16,20] is hyper-static and solicits control synchronization to avoid violation of geometric constraints. It also increases the demand for space and payload for additional actuators. Several works addressed this issue by pairing one active cable with a passive resetting mechanism (usually a torsion spring) to achieve bidirectional rotation [4,11], where the joint rotates away from the equilibrium point by pulling the cable, and recovers by the spring torque. One major concern of this configuration is that the magnitude of the recovery torque is merely dependent on the joint position, and thus cannot achieve high-bandwidth control [2,22]. In addition, this type of mechanism is vulnerable to external disturbances when regulated at a certain angle, as the stiffness of the spring is significantly smaller than the cable.

Driving two active cables with one actuator for bidirectional rotation can circumvent the stiffness issue of passive resetting mechanisms. Usually, a pulley with a circular track profile is deployed for cable retracting and releasing simultaneously. However, it has been addressed that a circular pulley can only be adopted when the change of rotation angle in the revolute joint is linear with respect to the change of cable length, and only a few specifically designed joint structures [6,10,17] can meet this requirement. However, the joint structure is often task-dependent, and the majority of cable-driven revolute joints cannot fulfill the linearity requirements [3,18]. The nonlinearity in these joints, if driven by pulleys with circular track profiles, leads to a gap between the lengths of retracted and released cables under the same rotation, causing slack or increased stress of certain cables, and furthermore, failures of the mechanism. Apart from the geometric mismatch of cables, the nonlinear relationship between the joint and motor rotations will also affect the performance of kinematic control [17]. Existing works adopted nonlinear control techniques [9,15] to address this matter, but the robustness and bandwidth are difficult to be guaranteed.

Therefore, the application of cable-driven revolute joints can be significantly enlarged, if the joint rotation can be actuated bidirectionally with one motor for high bandwidth while maintaining a linear kinematic relationship with the motor rotation. However, the configuration of the revolute joint is usually task-dependent and cannot be freely selected, so an actuation mechanism can be adapted for compensation between the joint and motor rotations. This paper proposes a novel actuation mechanism to drive the rotation of cable-driven revolute joints bidirectionally with one motor. A pulley with two independent non-circular tracks is designed to handle the geometric distinction between the two active cables for concurrent retraction and release, and the kinematic nonlinearity between the joint and cable. Both conditions are formulated as differential equations, of which the analytical solutions represent the set of candidates for feasible pulley track profiles.

Our contributions are summarized as follows:

- A novel actuation mechanism is proposed for general cable-driven revolute joints. This mechanism is able to use one motor to drive two active cables for bidirectional rotation, thus having high bandwidth compared with the configurations with one active cable and a resetting mechanism. It does not cause a significant change in the total above-the-ground cable length during rotation, which is common in circular pulleys and may cause cable plastic deformation, and furthermore failure of the mechanism. This mechanism also creates a linear relationship between joint and motor rotations.
- The effectiveness of the proposed mechanism is verified through simulation. Results show significant improvements in the constant cable length perseverance and the kinematic joint-to-motor linearity.

2 Design Methodology

2.1 Design Requirements

This section analyzes the concerns of cable-driven revolute joints in the geometric and kinematic senses and presents how these can be formulated as design requirements of the proposed actuation mechanism. Figure 1(a) shows a general configuration of the cable-driven revolute joints, of which the rotation is driven by the two active cables on its two sides. When actuated by one actuator, the two active cables are winded on two separate tracks of one pulley installed on the motor, each of which has a schematic shown in Fig. 1(b). It should be noticed that although the presented joint has geometric symmetry for simplicity, all proposed analysis and design procedures in this paper can easily facilitate the asymmetric configurations by designing two track profiles separately.

Geometrically, the cable lengths of the two active cables vary at different rotation positions. For joint angle θ, define the total above-the-ground cable length $L(\theta)$ as

$$L(\theta) = l_L(\theta) + l_R(\theta), \tag{1}$$

where $l_L(\theta)$ and $l_R(\theta)$ are denoted in Fig. 1(a), and calculated as

$$l_L(\theta) = \sqrt{h^2 + w^2 + a^2 - 2a\sqrt{h^2 + w^2}\sin(\alpha + \theta)} \tag{2}$$

and

$$l_R(\theta) = l_L(-\theta) \tag{3}$$

for the symmetric configuration. Here h, w, a and α are dimensional parameters of the joint defined in Fig. 1 (a) and can be selected upon specific task requirements.

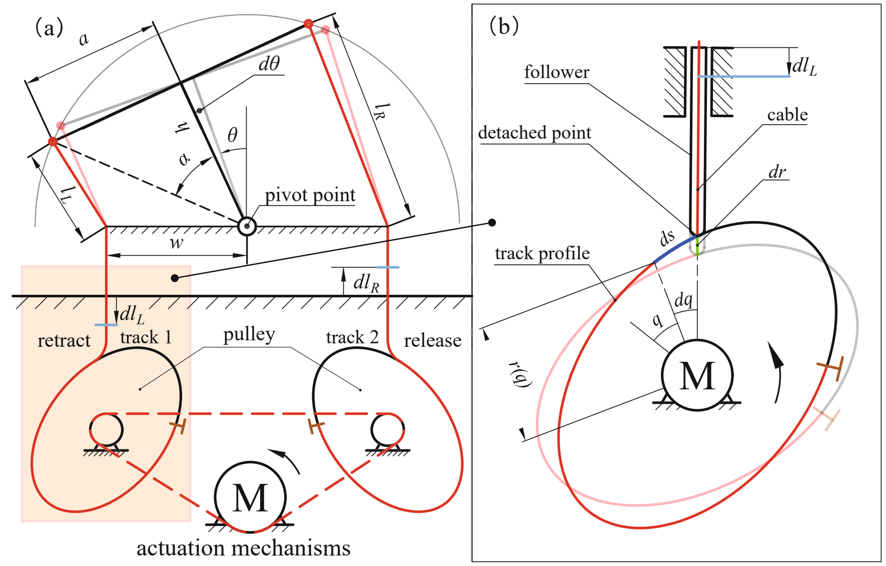

Fig. 1. Schematics of the cable-driven revolute joint and the actuation mechanism. (a) Schematic of a general cable-driven revolute joint. The rotation is controlled by the two active cables on the two sides. When the joint rotates $d\theta$ counterclockwise, a length of dl_L is retracted on the left cable, and a length of dl_R is released on the right cable accordingly. Due to the nonlinear transmission between the cable and joint motions, $|dl_L| \neq |dl_R|$ in general. Notice that the joint may be asymmetric on the left and right sides depending on specific tasks. (b) The actuation mechanism, by which one active cable (the left cable in the figure) is controlled for retraction and release. The cable is winded on the track profile of the pulley. A follower presses the cable on the track to fix the detached point. The pulley is installed on the motor rotor. The retraction and release of one active cable are realized by rotating the motor in two directions. When the pulley has two separate tracks on which the two active cables are winded, the revolute joint can be controlled with one motor for bidirectional rotation.

It can be verified that, within the operational range of the revolute joint $\theta \in (\alpha - \pi/2, \pi/2 - \alpha)$, the total above-the-ground cable length $L(\theta)$ is nonlinear, and has a single global minimum at $L(0) = 2h$. Therefore, when initiating at the equilibrium joint angle ($\theta = 0$), any rotation requires additional cable length to compensate for the increase of $L(\theta)$, or the cables will be stretched, further resulting in potential plastic deformation or disruption. Reversely, when initiating at a large joint angle, backward rotation decreases the total above-the-ground cable length, which may cause the mechanism to derail and stuck if not properly absorbed. The pulley with the circular track profile, in this scenario, is not applicable as it can only handle constant or linear total above-the-ground cable length $L(\theta)$ by adopting tracks of identical or proportional radius respectively.

Therefore, according to the geometric concern on cable length variation, we propose

- **Condition 1:** The proposed mechanism shall follow the change of total above-the-ground cable length $L(\theta)$ in equation (1) and make compensation accordingly to decrease the change of cable tension at different joint angles.

The schematic of the actuation mechanism is shown in Fig. 1(b), where a follower is applied to constrain the detached point. The pulley track radius at motor angle q is denoted as $r(q)$, while the length of the track profile from the initial angle to q is denoted by $s(q)$. The compensation is realized by tracking the length change of $l_L(\theta)$ and $l_R(\theta)$ with the two pulley tracks accordingly. For the symmetric configuration, the two tracks are identical, and we only discuss the one associated with $l_L(\theta)$ for compactness. However, it should be emphasized that the procedure can be directly applied in asymmetric joint configurations by calculating the two tracks independently.

Perturbing the joint angle θ with a small increment $d\theta$ leads to a variation of $dl_L(\theta)$ in $l_L(\theta)$, as shown in Fig. 1(a). The cable length variation is compensated by the change of cable length on both the pulley and the follower, as in Fig. 1(b),

$$dl_L(\theta) + ds(q) + (-dr(q)) = 0. \tag{4}$$

Kinematically, taking the derivative of equation (2) yields how the angular velocity of joint angle is dependent on the speed of cable retraction/release as

$$\frac{d\theta}{dt} = -\frac{l_L(\theta)}{a\sqrt{h^2+w^2}\cos(\alpha+\theta)}\frac{dl_L(\theta)}{dt}. \tag{5}$$

When actuated by the pulley, the speed of cable retraction/release can be further associated with the rotation speed of the motor as

$$\frac{dl_L(\theta)}{dt} = g(\theta)\frac{dq}{dt}, \tag{6}$$

where the $g(\theta)$ function depicts how the cables are winded on the pulley and are determined merely on the pulley track profile.

Therefore, the relationship between the revolute joint and motor rotations can be expressed as

$$\frac{dq}{dt} = K_r(\theta)\frac{d\theta}{dt}, \tag{7}$$

where the kinematic factor $K(\theta)$ has a form of

$$K_r(\theta) = -\frac{a\sqrt{h^2+w^2}\cos(\alpha+\theta)}{g(\theta)l_L(\theta)}. \tag{8}$$

Therefore, to address the kinematic concern on the nonlinear relationship of joint and motor rotations, we propose

- **Condition 2:** The kinematic factor $K(\theta)$ shall be constant to facilitate high-performance control of joint rotation.

In the equation form,

$$dq = K_r d\theta, \tag{9}$$

where K_r is a selected constant parameter based on dimensional, kinematic, and power constraints for specific tasks. It should be noticed that the $g(\theta)$ functions of circular pulleys are constant and cannot compensate for the nonlinearity in (8).

In the rest of this paper, we denote

$$\ddot{r}(q) = \frac{d^2}{dq^2} r(q),\ \dot{r}(q) = \frac{d}{dq} r(q) \tag{10}$$

for notation simplicity.

2.2 Analytical Solution When the Ratio of $\dot{r}(q)$ and $r(q)$ Is Small

The two equality conditions (4) and (9) can jointly formulate an ordinary differential equation (ODE) of $r(q)$ with respect to q

$$r(q)\sqrt{1+(\frac{\dot{r}(q)}{r(q)})^2} - \dot{r}(q) - \frac{1}{K_r}\frac{a\sqrt{h^2+w^2}\cos{(\alpha+\frac{q}{K_r})}}{\sqrt{h^2+w^2+a^2-2a\sqrt{h^2+w^2}\sin{(\alpha+\frac{q}{K_r})}}} = 0, \tag{11}$$

given that the pulley track profile segment $ds(q)$ can be calculated using the Pythagorean theorem as

$$ds(q) = \sqrt{r^2(q)+\dot{r}^2(q)}dq. \tag{12}$$

From equation (11), it can be observed that if the pulley track radius changes relatively slow with respect to the motor rotation q, or

$$(\frac{\dot{r}(q)}{r(q)})^2 \leq \epsilon^2 \ll 1, \tag{13}$$

where ϵ^2 is a small number compared to 1, the ODE (11) can be approximated by

$$r(q) - \dot{r}(q) - \frac{1}{K_r}\frac{a\sqrt{h^2+w^2}\cos{(\alpha+\frac{q}{K_r})}}{\sqrt{h^2+w^2+a^2-2a\sqrt{h^2+w^2}\sin{(\alpha+\frac{q}{K_r})}}} = 0, \tag{14}$$

which has an analytical solution

$$r(q) = r_0 e^{(q-q_0)} + e^q \int_{q_0}^{q} f(\tau)d\tau, \tag{15}$$

for the boundary condition

$$r(q_0) = r_0, \tag{16}$$

and the integrand

$$f(\tau) = -\frac{1}{K_r}\frac{a\sqrt{h^2+w^2}\cos\left(\alpha+\frac{\tau}{K_r}\right)}{\sqrt{h^2+w^2+a^2-2a\sqrt{h^2+w^2}\sin\left(\alpha+\frac{\tau}{K_r}\right)}}e^{-\tau}. \tag{17}$$

2.3 Range of Boundary Condition r_0

In the real-world pulley track profile design, the value of r_0 cannot be freely selected, which is further bounded by two following constraints:

- **Constraint 1:** for a real-world mechanical mechanism, $r(q)$ should be positive within its domain. That is

$$r(q) = r_0 e^{(q-q_0)} + e^q \int_{q_0}^{q} f(\tau)d\tau > 0. \tag{18}$$

- **Constraint 2:** the assumption that the pulley track radius changes relatively slow with respect to the motor rotation q has to be guaranteed to get the analytical solution (15). Combining assumption math formula (13) and pulley track profile description equation (14), inequality set

$$\begin{cases} (1-|\epsilon|)r(q) - \dfrac{1}{K_r}\dfrac{a\sqrt{h^2+w^2}\cos\left(\alpha+\frac{q}{K_r}\right)}{\sqrt{h^2+w^2+a^2-2a\sqrt{h^2+w^2}\sin\left(\alpha+\frac{q}{K_r}\right)}} \leq 0 \\ (1+|\epsilon|)r(q) - \dfrac{1}{K_r}\dfrac{a\sqrt{h^2+w^2}\cos\left(\alpha+\frac{q}{K_r}\right)}{\sqrt{h^2+w^2+a^2-2a\sqrt{h^2+w^2}\sin\left(\alpha+\frac{q}{K_r}\right)}} \geq 0 \end{cases} \tag{19}$$

  should be satisfied.

3 Results and Simulation Verifications

3.1 Design Procedure

This section shows the design procedure of the proposed actuation mechanism with real-world parameters of revolute joints and cables, as shown in Table 1. The desired kinematic factor K_r is selected as 2.7. The driving cable uses the common 304 stainless steel as material.

The set of pulley track profiles that satisfies the equality constraints on geometric and kinematic concerns (4) and (9) is obtained by substituting the joint and design specifications into (15), as shown in Fig. 2(a). However, the boundary condition r_0 is further bounded by inequalities (18) and (19). Thus, the feasible solutions are shrunk to a small set.

Table 1. Specifications of revolute joint design and cable material

h	w	a	K_r	ϵ	Young's modulus	Yield strength
40 mm	18 mm	18 mm	2.7	0.3	200 GPa	215 GPa

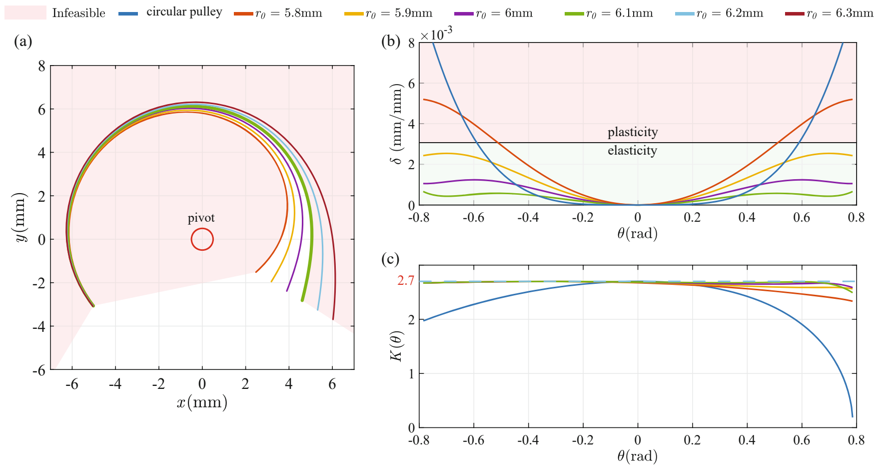

Fig. 2. The analytical solution set of pulley track profiles (15) satisfies the equality constraints (4) and (9). However, most of the pulley track profiles are infeasible since the boundary condition r_0 needs to satisfy inequalities (18) and (19). (b)(c) Comparison between the circular pulley and proposed mechanism in both geometric and kinematic aspects. The pulley track profile corresponding to the best result is bold in (a).

3.2 Simulation Verifications

This section aims to verify that the proposed mechanism indeed elevates the performance in the geometric and kinematic aspects by fulfilling the two equality constraints (4) and (9) respectively. Notice that although the pulley track profile is selected from the analytical solution set (15), which is obtained by jointly solving the two equality constraints, errors may arise from the approximation (13).

For the geometric constraint (4), the real above-the-ground length $\widetilde{L}(\theta)$ is calculated as

$$\widetilde{L}(\theta) = \int_0^{\theta} (ds + dl_L - dr) + \int_0^{-\theta} (ds + dl_L - dr) + L(0). \tag{20}$$

Assuming that the revolute joint is initialized at $\theta = 0$, the relative cable length change δ can be defined as

$$\delta = \frac{\widetilde{L}(\theta) - L(0)}{L(0)}. \tag{21}$$

For the kinematic constraint (9), the real kinematic factor $K(\theta)$ can be calculated as

$$K(\theta) = \frac{dq}{-ds + dr}. \tag{22}$$

The comparison of the proposed actuation mechanism with the circular pulley is shown in Fig. 2(b) and (c). It can be observed that the length change of the circular pulley, which may cause plastic deformation for certain materials as in this case, has been largely compensated by the proposed mechanism. The significance will be reinforced when the cable is preloaded. This is the direct evidence to show that the proposed mechanism can enable one motor to drive bidirectional rotation of cable-driven revolute joints. Figure 2(c) compares the kinematic performance of the proposed mechanism with the circular pulley of the corresponding radius. The result shows that the kinematic linearity is greatly improved, and the designed kinematic transmission ratio is achieved. The solution of the pulley track profile that leads to the best result is bold in Fig. 2(a).

4 Discussion

One key feature of the proposed mechanism is that the bidirectional linear rotation enables high-bandwidth control and high stiffness regulation in both directions, especially compared with the mechanisms consisting of one active cable and a resetting mechanism. This characteristic is critical in applications regarding highly dynamic requirements, including robotic positioning [3], robotic tail [16] and manipulators [14,20]. However, it should be noticed that the resetting mechanism is a simple yet effective solution for applications with requirements on only unidirectional motions such as grasping [1,11], and even advantageous with flexibility and safety concerns such as invasive medical tools [21].

Another key feature of the proposed mechanism is that the bidirectional rotation with two active cables is driven by one actuator, which reduces the number of actuators required for such configurations and avoids the synchronization issue in contrast with the conventional mechanisms where each active cable is driven with an independent motor [3,14,16,20]. Compared with other existing works which achieve bidirectional rotation with one actuator [6,10,12,17], the proposed mechanism does not have requirements on the shape and size of the revolute joint. Different revolute joints share the same design procedure in our proposed framework with different descriptions of the l_L and l_R functions.

5 Conclusion and Future Work

This paper proposes a novel actuation mechanism to drive the bidirectional rotation of a general cable-driven revolute joint with one motor. A pulley with two non-circular track profiles is designed to handle the different length changes on the two active cables and create a linear kinematic relationship between the motor and the joint rotations. The mechanism has high system bandwidth compared with the configurations with one active cable and a resetting mechanism.

A systematic design procedure is proposed to design the pulley track profiles based on joint parameters and desired kinematic relations. The design procedure is reviewed by a numerical example, and the effectiveness of the proposed mechanism is verified in both geometric and kinematic senses in contrast with the conventional pulley with the circular track profile.

It should be also noticed that the result in Fig. 2(b) may also cause the plastic deformation given a specific ϵ. This may alleviate the efficiency of the proposed method since every solution needs to be carefully verified by numerical simulations. In future work, we will formulate the whole design producer as an optimization problem, which can directly output the optimal r_0 value.

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