Cable Traversing Robots on Spatially Structured Cableway for Reconfigurable Parallel Cable System

○Randy Raharja SUDIONO, Student Member, Tokyo Institute of Technology, sudiono.r.aa@m.titech.ac.jp
Yusuke SUGAHARA, Member, Tokyo Institute of Technology
Mitsuru ENDO, Member, Nihon University
Daisuke MATSUURA, Member, Tokyo Institute of Technology
Yukio TAKEDA, Member, Tokyo Institute of Technology

In conventional configuration of Parallel Cable Mechanism, anchors (winding machines) were fixed and practically used in structured environment. In an attempt to reduce the hurdle of the above application in an unstructured environment, a concept of spatially structured cableway with traversing mobile anchors on it is proposed in this paper. Technical challenges lie in the strategy for mobile anchors to traverse between branched cable, the reconfiguration of parallel mechanism by anchors' position, and the method to control the reconfigured parallel cable mechanism. A cableway network that follows a spatially structured polygonal chain is proposed. Prototypes consisting of Remote Center-of-Motion Mechanism and dedicated wheel profile was proposed, manufactured, and its traversing capabilities between branched cables were then investigated through experiments. Furthermore, its applicability to reconfigure parallel cable mechanism by anchors' positioning is demonstrated in this paper.

Key Words: Cable-Driven Parallel Robot, Field Robotics, Cable Traversing Robot

1. Introduction

This paper proposes an application of field robotics involving cableways as a track which is capable of providing similar constraint and support as railings and its adaptability to its working environment. Moreover, cableways can be constructed as polylines that follows the landscape of natural environment which ensures minimal environmental damage. The applicability of cableway in agriculture and forestry management was also proposed by G. Notomista, et al. which stated cableways' capability of utilizing existing infrastructure or landscape[1]. The concept of cableway traversing robot is then elevated by incorporating parallel cable mechanism to achieve a lifting capability similar to drone with greater reliability and at the same time widening its practical application into monitoring aquatic ecosystem such as lakes.

In comparison to conventional parallel cable mechanisms with fixed anchors[2], the concept proposed in this paper consists of a system of parallel cable mechanism and mobile anchors as shown in Fig. 1, where the mechanism is situated in natural environment. Similar to the concept proposed by Yamamoto, et al. [3], mobile anchors are introduced to attain a reconfiguration capability for the parallel cable mechanism. These mobile anchors are constrained onto cableways constructed along the landscape of natural occurrences. Cableways will be maintained by sub-cables which are attached to several supporting pillars or existing topography of the environment. The mobile anchors consisting of cable traversing mechanism and winding machine will traverse on the cableway networks and manipulator cables from each anchor will manipulate the end-effector.

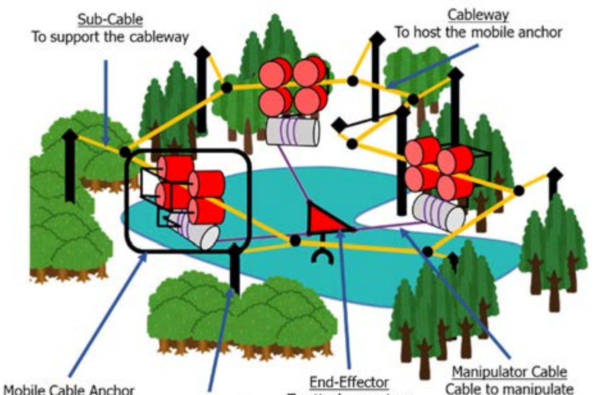

Fig. 1 Conceptual Design Proposed

The ultimate goal of this paper is to develop a concept of reconfigurable parallel cable mechanism by utilizing mobile cable anchor and cableway network structure. The work scope of this paper, however, will cover the development of the mobile cable anchors necessary for the conceptual design above and demonstrate its feasibility.

2. Development of Mobile Cable Anchors

This section will discuss the required functions, conceptual design, and manufactured prototypes.

2.1 Technical Challenge and Required Functions

There are two technical challenges author sets in this paper, first is to develop the mobile anchor for proposed system, and second is to demonstrate the feasibility of the mobile anchor proposed in attaining Reconfigurable Parallel Cable Mechanism.

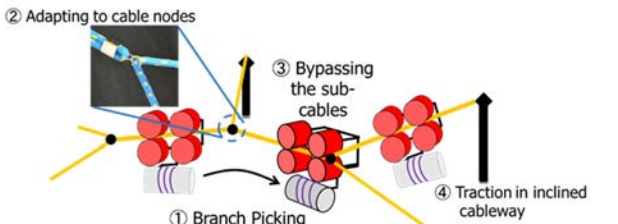

Fig. 2 Functional Requirements

There are four minimum functions required for mobile anchors:

① Ability to perform branch picking
② Ability to adapt to the cable nodes
③ Ability to bypass sub-cables
④ Ability to run on top of inclined cableway

An illustration of functional requirements is shown in Fig. 2. The necessity of the first function is quite clear because the mobile anchor needs to travel along polygonal chain of cableway. Cable elements such as clamps are necessary to maintain the structure of the cableway, causing nodes in branches which led to second necessary function. Unlike conventional ropeways where main propeller is the rope or cable, the structure of the mechanism will consist of a set of wheels that runs on cableway to allow self-propelling. The third function, the capability to bypass sub-cables is necessary to prevent physical interference of the mobile anchor and cableway during branch picking. Lastly, to allow implementation in unstructured landscape, therefore it is necessary for the mechanism to traverse in inclined and downslope cableway.

2.2 Design Specification and Parameter

The cable used to test the prototype is a 6 mm Dyneema cable. Steel ring (ϕ 10 mm) and aluminum ring (ϕ 12 mm) are deformed and arranged as shown in Fig. 3 to form a cable node. Although the reliability of the nodes structure proposed has not been reviewed, the author found that aluminum ring provided just enough durability for the experiment conducted in this paper. The other parameter for the mobile anchor developed is summarized in Table 1.

2.3 Elements of Mobile Anchor

The mobile anchor requires two vital elements. First is a dedicated wheel profile, and second is the Remote Center-of-Motion Mechanism. Unlike conventional design of cable robots where wheels are physically constrained from both sides, the driving wheels proposed is structured as cantilever. Remote center of motion mechanism is introduced to allow the wheels to rotate around the cableway without physical rotational joint

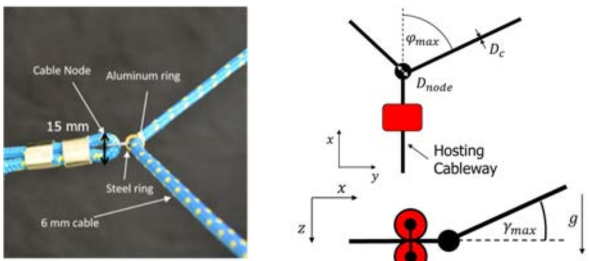

Fig. 3 Cable Nodes, Tilting, and Inclination Parameter

at the actual desired pivot location.

2.3.1 Wheel Profile

A dedicated wheel profile was designed with four important traits, as shown in Fig. 4. The asymmetric wheel groove contributes to branch picking and tilting. Cable teeth contributes to bypassing sub-cables. Wheel gap is designed to pass the cable nodes. Lastly, wedge is included to provide enough traction in inclined cableway.

Here, H_{gap} is the size of the wheel gap, D_{node} is the size of the cable node, α_w is the wedge angle, μ_s is the coefficient of static friction between cableway and wheel, D_t it the teeth

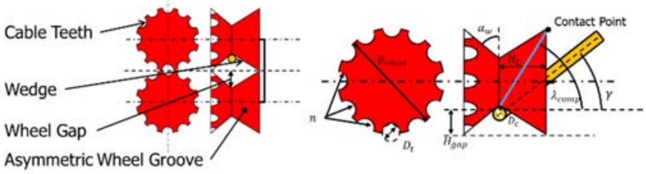

Fig. 4 Wheel Profile Design and Parameter

diameter, D_c is the cable diameter, $D_{contact}$ is the contact distance from the cableway to the end of the wheel groove, H_L is the longer length of asymmetric wheel groove, and λ_{comp} is compensation angle to allow passive tilting. Geometric conditions for wheels:

1. Passing the cable nodes

$$2H_{gap} \geq D_{node} \tag{1}$$

2. Traction during inclination

$$\sin \alpha_w \leq \frac{\mu_s}{\sin \gamma_{max}} \tag{2}$$

3. Bypassing Sub-cables

$$D_t \geq D_c \tag{3}$$

4. Branch picking/passive tilting

$$D_{contact} = \sqrt{{H_L}^2 + \left(D_{wheel} - H_{gap}\right)^2} \tag{4}$$

$$H_L = D_{contact} \cdot \cos\left(\lambda_{comp}\right) \tag{5}$$

Passive tilting is a condition where a contact between the inner side of the wheel groove with the desired branch causes enough torque to tilt the mobile anchor to be aligned with cableway's direction. This function can be achieved by rotating the wheel against its hosting cableway to a certain angle λ_{comp},

Table 1 Design Specifications

Parameter	Value
Max Node Dimension(D_{node})	15 mm
Cable Diameter(D_c)	6 mm
Maximum Inclination(γ_{max})	30°
Maximum Tilting Angle(φ_{max})	90°

allowing the desired branch to be in contact with the groove, resulting in contact force against the wheel.

Table 2. Design Parameter of Wheel's Profile

Parameter		Value
n	Number of Constraining Teeth	2
D_{wheel}	Wheel Diameter	60 mm
α_w	Wedge angle	13.5°
D_t	Teeth Diameter	8 mm
H_{gap}	Gap Distance	11 mm
μ_s	Coef. of static friction	0.12
λ_{comp}	Compensation angle for passive tilting	65°
H_L	Lower Height	22 mm

2.3.2 Remote Center-of-Motion Mechanism

The Remote Center-of-Motion Mechanism (RCM Mechanism) consists of a set of spherical linkages arranged such that all axis vector of rotational couples intersects at one point called the virtual pivot. This paper proposes a concept using a 3R Spherical Linkage with driving wheels attached at its end as shown in Fig. 4 for function ①, ③, and ④. The end-effector of this spherical linkages is the axis vector of the cable teeth which can be represented by vector τ in Fig. 8.

According to [4], the vector z_c can be calculated from the angle parameter of spherical linkage α_1 and α_2, and the input angle of actuator A and B, θ_A and θ_B:

$$\overrightarrow{z_c} = [Z(\theta_1)][Y(\alpha_1)][Z(\theta_2)][Y(\alpha_2)]\overrightarrow{k_c} \qquad (6)$$

Where $Y(x)$ represents rotational transformation matrix along y axis, and $\overrightarrow{k_c}$ is local z axis vector of actuator C with value of $[0 \quad 0 \quad 1]^t$. Thus, vector τ can be represented as:

$$\vec{\tau} = -[Z(\theta_1)][Y(\alpha_1)][Z(\theta_2)][Y(\alpha_2)]\overrightarrow{k_c} \qquad (7)$$

Projecting these vectors into an arbitrary sphere surface, for $\alpha_1 = 90°$ and $\alpha_2 = 90°$, the workspace of the RCM mechanism used in this paper is shown in Fig. 5.

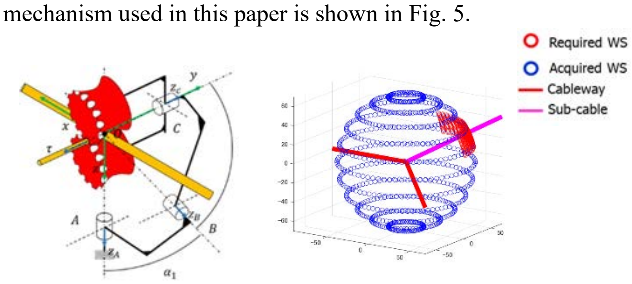

Fig. 5 Remote Center-of-Motion Mechanism and Workspace

2.4 Dual Arm Type

Dual arm type is a type utilizing two sets of RCM mechanism and driving wheels arranged as shown in Fig. 6. This mechanism is sufficiently constrained to the cable allowing pose control and greater load limit capability.

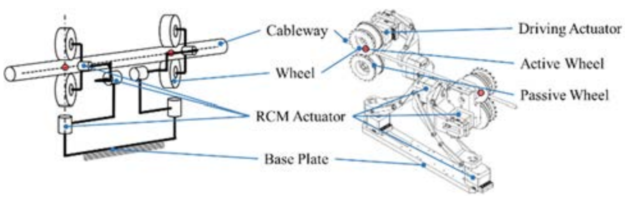

Fig. 6 Kinematic Diagram and 3D Model of Dual Arm Type

2.5 Single Arm Type

Single Arm type consists of only one pair of RCM Mechanism arranged as shown in Fig. 7. This mechanism is an under-constrained mechanism. The under-constrained condition will be utilized to allow the mechanism to tilt passively. Compared to dual arm mechanism, single arm type is relatively simple in control, and uses less actuator in cost of its constraint against the cable, causing the mechanism's pose to be greatly affected by its Centre-of-Gravity shift.

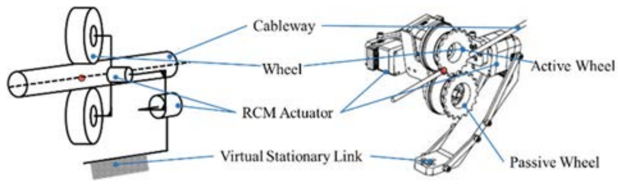

Fig. 7 Kinematic Diagram and 3D Model of Single Arm Type

3. Experimental Results

This section will discuss on the functional capability of both prototypes and feasibility of proposed mechanism.

3.1 Climbing Experiments

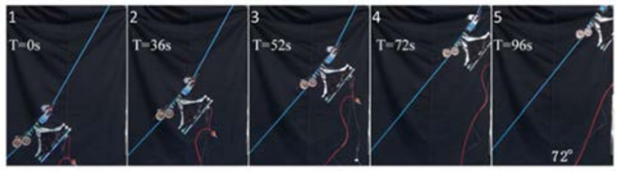

Fig. 8 Dual Arm Type on Inclined Cable

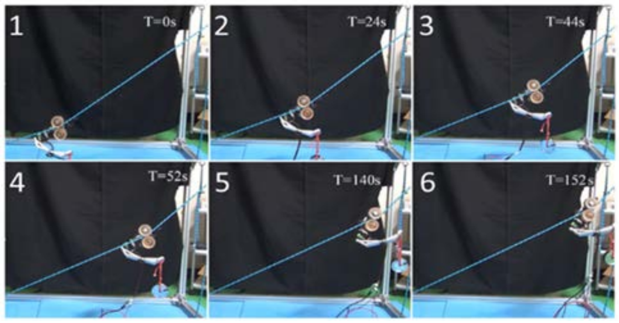

Fig. 9 Single Arm Type on Inclined Cable
(Frame 4→no tension, frame 5→tensioned)

The climbing environment is a simple inclined cableway where the mechanism is conditioned to run on it. The purpose of experiment is to investigate and compare the capability of dual arm and single arm type on inclined cable with tensioning and coating. Tensioning is a method to improve climbing capability by actuating the redundant actuator C from the RCM mechanism such that both wheels are in contact to the cableway creating tensions. Another method to improve climbing capability is by coating wheels' surface. With tensioning, single arm type was able to climb up to 52° and 72° for dual arm type.

3.2 Planar Tilting Experiment

The experiment environment is a planar three-way branching cable. The dual arm type and single arm type traverses from one branch to another. Dual arm type possesses good posture control in exchange to its quite complex and time-consuming tilting procedure. On the contrary, the single arm type is able to tilt passively in exchange to its constraining capability to the cableway. Up to 80° tilting for the single type and 85° tilting for the dual type is confirmed.

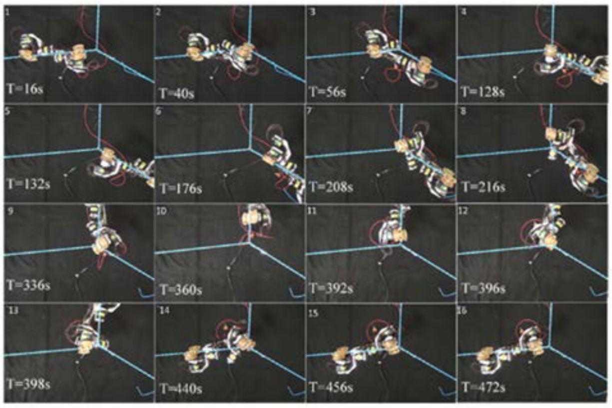
Fig. 10 Dual Arm Type on Planar Tilting

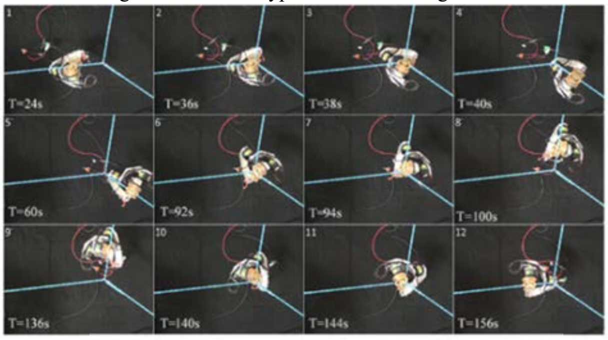
Fig. 11 Single Arm Type on Planar Tilting

3.3 Spatial Tilting Experiment

The experiment environment for spatial tilting is a three-way cable conditioned in spatial environment. Both the dual arm type and single arm type could traverse toward inclination and downslope to identify its capability in spatial environment.

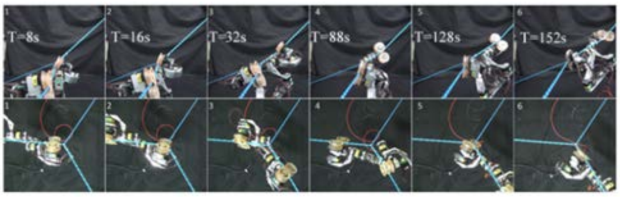
Fig. 12 Dual Arm Type on Spatial Tilting

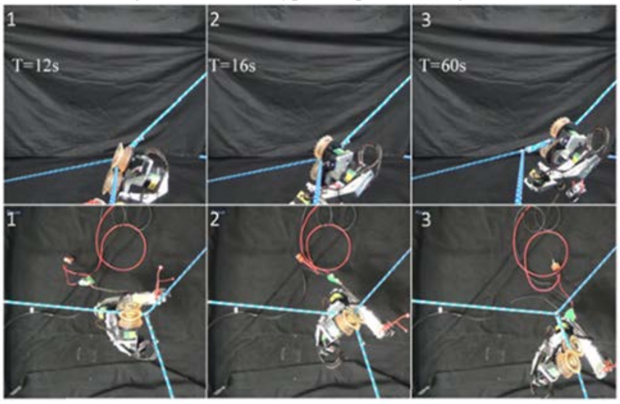

Fig. 13 Single Arm Type on Spatial Tilting

3.4 Result Summary

Below is the summary of the experiment based on Table 3:

- Tensioning is a better solution to improve traction
- Dual Arm Type provides better pose control and needed a more complex procedure during tilting
- Single Arm Type uses simpler pose control due to passive tilting
- Dual Arm Type is prone to physical interference

Table 3. Summary of Experiment Results

Result	Dual Arm	Single Arm
Climbing Capability		
No Condition	32°	28°
With Coating	41°	37°
Tensioning	72°	52°
Planar Tilting		
Maximum Tilting	85°	80°
Spatial Tilting		
Inclined	48°	37°
Downslope	37°	27°
Maximum Tilting	63°	75°

3.5 Reconfiguration of Parallel Cable Mechanism

Using two single arm mechanism and winding anchors, the feasibility of the prototype and wheel design proposed is demonstrated as shown in Fig. 14. Three positioning control and one pose control capability is confirmed through this experiment.

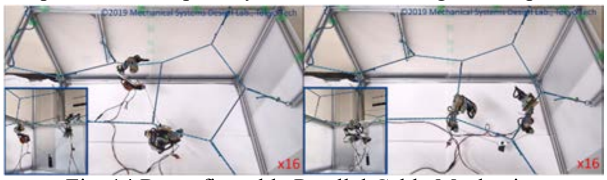
Fig. 14 Reconfigurable Parallel Cable Mechanism

4. Conclusion and Future Works

This paper proposed a cableway traversing robots in spatial environment which can be utilized as Mobile Anchors for RPCM or directly as field robots. Several future works such as sensing system and better infrastructure for cable nodes is necessary for this concept to achieve its full potential.

Acknowledgements

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References

[1] G. Notomista, Y. Emam and M. Egerstedt, "The SlothBot: A Novel Design for a Wire-Traversing Robot," IEEE Robotics and Automation Letters, vol. 4, no. 2, pp. 1993-1998, April 2019.

[2] Gosselin, C. "Cable-driven parallel mechanisms: state of the art and perspectives." Mechanical Engineering Reviews 1.1 (2014): DSM0004-DSM0004.

[3] Yamamoto, M., Yanai N., and Mohri, A. "Trajectory control of incompletely restrained parallel-wire-suspended mechanism based on inverse dynamics." IEEE transactions on robotics 20.5 (2004): 840-850

[4] McCarthy, J. M. Geometric design of linkages. Vol. 11. Springer Science & Business Media, 2006.