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A Suspended Cable-Driven Parallel Robot for Human-Cooperative Object Transportation

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Abstract. This paper describes the development of the suspended cable-driven parallel robot for object transportation having power assist function. The robot consists of the winches to drive four cables which suspend the object and control its three degrees of freedom motion. The impedance controller based on the external force measured by the tension sensors enables the operator to transport and position the object intuitively by directly applying the force to the object. Additionally, the workspace departure avoidance control by installing the virtual stiffness into the controller is also introduced.

Keywords: Cable-driven parallel robot · Power assist · Impedance control

1 Introduction

In recent years the reduction of the labor force has caused many problems in maintaining social systems. The necessity of productivity improvement is advocated in all industrial fields, and expectations for utilization of robot technology are increasing. Above all, in the construction industry, where labor shortages are serious, the introduction of robot technology is accelerating [1].

Especially, there is a strong demand for labor saving in heavy load transportation and positioning on site. Overhead traveling cranes are commonly used to transport heavy objects, and researches on vibration suppression control have been widely conducted for a long time [2]. However, the stiffness in the horizontal plane is zero in principle, so its automatic positioning is difficult in practice. For the transportation of heavy objects with fine positioning, practical use of systems using robot technology has recently started. ATOUN Model K [3], developed by ATOUN Inc. in collaboration with Shimizu Corp. and SC Machinery Corp., is a robot for assistance in bar arrangement work. This is a serial link type power assist arm that can be mounted on a pillar at a construction site. The operator directly applies force to the bar raised by the robot's hands, enabling intuitive

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and smooth handling of the target object. This can be considered as an extension of the existing power assist arm called "Balancer" [4] that has been used for more general purposes. Both of these structures are serial link type arm and requires an extremely long link length for the transportation and positioning over a wide area like cranes.

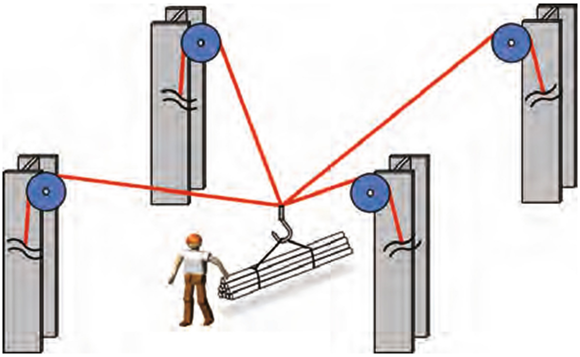


Fig. 1. Conceptual image.

The cable-driven parallel robot (CDPR) is advantageous for such a wide range of transport and positioning [5]. For example, Pott et al., has been investigating a construction system for a solar power plant using CDPR [6]. Above all, the suspended CDPR is considered to have a high affinity for construction sites because its structure is similar to a crane. The application fields of the pioneering suspended CDPR, NIST ROBOCRANE, were the sites of shipbuilding and construction [7]. The superiority over traditional cranes is also claimed in the study of CDPR by Yamamoto et al. in which three mobile trolleys suspend the end effector with parallel cables [8].

The authors' long-term objective in this study is to develop a suspended CDPR for the transportation and positioning of heavy objects on construction sites, as shown in Fig. 1. This is a suspended CDPR which consists of four winches attached on the upper portion of steel columns in a building under construction like the ATOUN Model K, and four wires reeled out from it. The four wires are connected at one point to form an end effector, and the object is hung at this point. Therefore, the posture of the object is not constrained. The movable range is a cuboid with a rectangle connecting the four wire feeding points as its upper surface, and a wider movable range can be easily obtained than the serial link type. The stiffness in the horizontal plane is higher than the overhead traveling crane, which is advantageous for fine positioning. In addition, this system has a power assist function, and the operator can intuitively transport and position the object by directly applying force to itself.

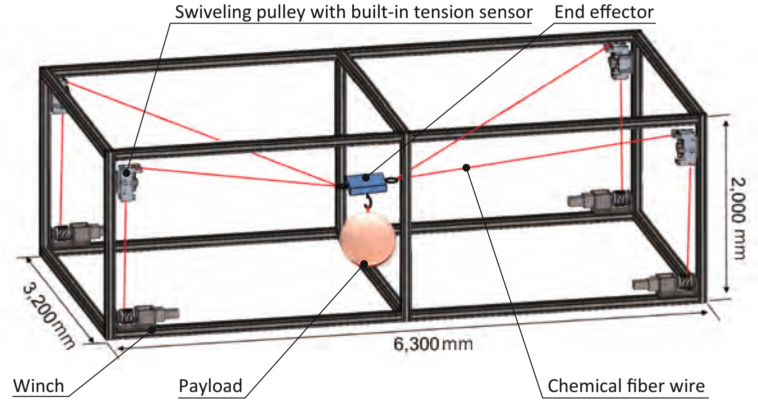
A pioneering study of a similar concept is the Power-Assist Lifting Device [9] by Hayatsu et al. Although the number of wires and the degrees of freedom are different, this was a suspended CDPR composed of five chain blocks and realized the positioning of heavy objects by power assist using damping control.

In this study, the position based impedance control which is more general and its parameter tuning is intuitive is utilized. Furthermore, by introducing a virtual potential field, a control to prevent departure from the workspace is realized.

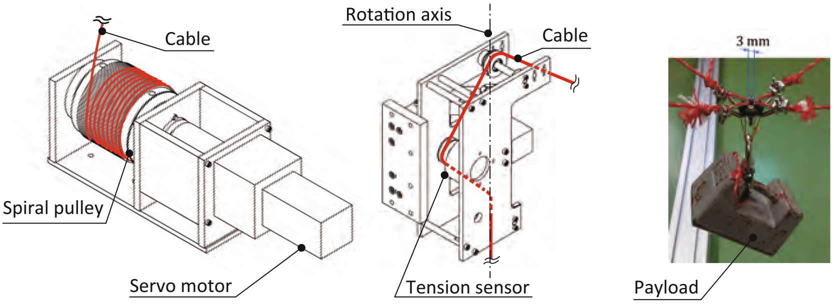
2 Prototype

The mechanical structure and specifications of the suspended CDPR prototype named TKSC78 (Tokyo Tech Kajima Suspended Cable-Driven Parallel Robot – No. 78) developed in this study are shown in Fig. 2 and Table 1, respectively.

As shown in (a) in the figure, this robot is a redundant three degrees-of-freedom suspended CDPR in which four cables suspended from four frame anchors on the upper corners of an outer cuboid frame simulating the steel columns in a construction site are connected at one point which is used as the end effector. The winches for winding the cables are fixed at the lower portion



(a) Overall structure



(b) Winch (c) Swiveling pulley (d) End effector

Fig. 2. Structure of TKSC78 prototype.

of the frame, and the winches control the lengths of the cables by driving the spiral pulleys with servo motors as shown in (b) in the figure. The swiveling pulleys shown in (c) in the figure are fixed on the upper portion of the frame as frame anchors, have tension sensors which measure the tension of the cables, and have a function of passively rotating around the Yaw axis according to the cable tension. There is a sufficient distance between the winch and the swiveling pulley so that the fleet angle is less than 1.5°, which eliminates the need for a special mechanism to prevent the irregular winding. The end effector is equipped with a hook for hanging the object as shown in (d) in the figure.

Table 1. Specifications.

Model No.	TKSC78
Length × Width × Heigh	3200 × 6300 × 2000 mm
Degrees of freedom	3 Translational DOFs
Maximum payload	40 kg
Workspace	3000 × 6000 × 1000 mm
Maximum velocity	0.5 m/s

The control system is configured using INTime and EtherCAT. The servo driver operates in the position control mode, and position feedback control is performed inside the servo driver. The control program, which is a user application, acquires the angles of all the actuators and the values of the tension sensors in a control cycle of 5 ms, and commands the target angle of each actuator based on the computation by the control algorithm.

3 Controller

In this study, power assist control using position-based impedance control, also known as admittance control, is performed to realize the intuitive transportation and positioning by the operator directly applying force to the object. Furthermore, by extending this method and introducing a virtual potential field, a function to prevent departure from the workspace is realized. The block diagram of the control system is shown in Fig. 3.

As an example of using impedance control in CDPR, Osumi et al. proposed a crane with seven actuators which include a suspended parallel cable structure [10], and realized a peg-in-hole task by introducing compliance control [11]. There are also other studies that introduce admittance control to CDPR [12,13].

3.1 Power Assist Using Impedance Control

In this prototype, as described above, each servo driver operates in a local position control loop, so it has been necessary to set up a position control-based control system. Various methods of force control of robot manipulator have been

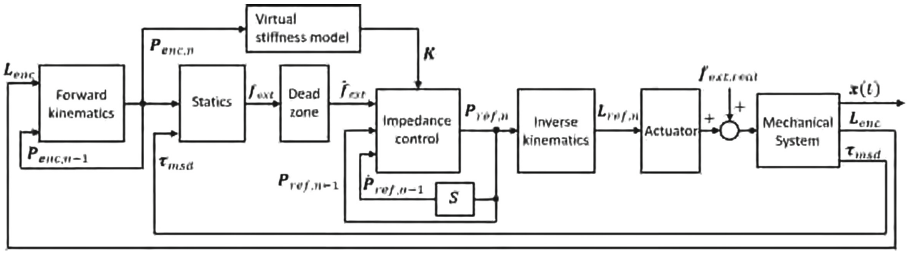


Fig. 3. Block diagram of the controller.

proposed, but for this reason, authors decided to use position control based impedance control. Assuming that only the actuation force from cables, the gravitational force and the operation force from operator act on the load, the actuation force from cables $\boldsymbol{f}_{wire} \in \mathbb{R}^3$ are as follows:

$$\boldsymbol{f}_{wire} = \boldsymbol{A}^T \boldsymbol{\tau} \tag{1}$$

where $\boldsymbol{\tau} \in \mathbb{R}^4$ is wire tension vector, $\boldsymbol{A}^T$ is the transpose of the Jacobian matrix referred to as *structure matrix* [14,15].

When only static transport is considered, the inertial force on the object is negligibly small compared to gravity, so the actuation force $\boldsymbol{f}_{wire}$, gravitational force $\boldsymbol{G} \in \mathbb{R}^3$, and the operating force $\boldsymbol{f}_{ext} \in \mathbb{R}^3$ applied by the operator can be considered to be balanced, and this relationship can be used to estimate the operating force:

$$\boldsymbol{f}_{wire} + \boldsymbol{f}_{ext} + \boldsymbol{G} = \boldsymbol{0}. \tag{2}$$

However, since inertial force is actually applied, a dead zone according to the weight of the object is provided to prevent vibration as follows:

$$\hat{\boldsymbol{f}}_{ext} = \begin{cases} \boldsymbol{0} & (|\boldsymbol{f}_{ext}| < \lambda|\boldsymbol{G}|) \\ \boldsymbol{f}_{ext} & (|\boldsymbol{f}_{ext}| \geq \lambda|\boldsymbol{G}|) \end{cases} \tag{3}$$

where $\hat{\boldsymbol{f}}_{ext} \in \mathbb{R}^3$ is the estimated value of the operating force with the dead zone applied, λ is the dead zone coefficient.

Let the object have a desired impedance characteristic represented by the following equation:

$$\boldsymbol{M}\ddot{\boldsymbol{P}} + \boldsymbol{C}\dot{\boldsymbol{P}} + \boldsymbol{K}\boldsymbol{P} = \hat{\boldsymbol{f}}_{ext} \tag{4}$$

where $\boldsymbol{P} \in \mathbb{R}^3$ is the position vector of the end effector, $\boldsymbol{M}$ is a virtual inartial matrix, $\boldsymbol{C}$ is a virtual viscous matrix, $\boldsymbol{K}$ is a virtual stiffness matrix, each of which is a diagonal matrix.

By discretizing Eq. (4), the acceleration of the end effector at the time of n sampling is as follows:

$$\ddot{\boldsymbol{P}}_n = \boldsymbol{M}^{-1}(\hat{\boldsymbol{f}}_{ext} - \boldsymbol{C}\dot{\boldsymbol{P}}_{n-1} - \boldsymbol{K}\boldsymbol{P}_{n-1}) \tag{5}$$

where $\dot{\boldsymbol{P}}_{n-1}$ and $\boldsymbol{P}_{n-1}$ are velocity vector and position vector of the end effector at the time of $n-1$ sampling.

By integrating these, the position vector of the end effector at the time of n sampling is obtained as follows:

$$\begin{aligned} \dot{\boldsymbol{P}}_n &= \dot{\boldsymbol{P}}_{n-1} + \Delta t \ddot{\boldsymbol{P}}_n \\ \boldsymbol{P}_n &= \boldsymbol{P}_{n-1} + \Delta t \dot{\boldsymbol{P}}_n \end{aligned} \tag{6}$$

where Δt is the control cycle.

Based on this, the length of each cable is computed by inverse kinematics, and is commanded to each servo driver.

This method has the advantage that parameter tuning is intuitive and suitable for site work, and has more expandability than stiffness control and damping control. For example, to realize a power assist to transport an object based on the force applied by the operator, it is enough to introduce only the virtual inertial matrix and the virtual viscous matrix and set the virtual stiffness matrix to 0. But the use of the repulsive force is also effective in some cases as described later.

3.2 Workspace Departure Avoidance Control Using Potential Field

This study proposes a system to transport and position heavy objects according to the operator's force, rather than transporting them automatically. This method is considered to be effective in a construction site where there are many obstacles and the situation changes every moment. However, since it is not easy for operators to handle huge objects with careful attention to collisions with obstacles and the movable range of the mechanism, the intuitive operation assist control is effective. In this study, for obstacle avoidance and departure prevention from the workspace, avoidance control using the potential method is introduced by using the virtual stiffness of the impedance control parameters.

Taking the Y axis direction as an example, let us consider a control which generates a virtual repulsive force when the end effector departs from available space set in consideration of the workspace of the mechanism. This is possible using the virtual stiffness k_y whose value depends on the end effector position y, as follows:

$$k_y = \begin{cases} 0 & (L_K < y < (Y_{max} - L_K)) \\ K & (y < L_K, (Y_{max} - L_K) < y) \end{cases} \tag{7}$$

where L_K is the equilibrium length of the virtual spring, Y_{max} is the length of the edge of the workspace.

By introducing this virtual stiffness into the impedance control law described above, as the end effector approaches the boundary of the workspace ($Y = 0$ and $y = Y_{max}$ in this example), the virtual potential of the output node increases, so the end effector behaves repulsively from the boundary of the workspace.

4 Experiments

To evaluate the hardware and controller proposed in this study, the object transportation experiment and avoidance control experiment have been done.

First, as an object transportation using impedance control, a series of transport operation, in which the end effector is attached to a 5.5 kg object placed on the floor, transported to the target position, removed from the object, and moved to another object position again, was performed. The parameters in this experiment are $C_x = C_y = 100, C_z = 40, M_x = M_y = 5, M_z = 40, \lambda = 0.03$, which have been determined heuristically.

Figure 4 shows a series of transportation operations. The operator carried the end effector while holding it directly by hand, and attached the object to the end effector. Next, impedance control was disabled once, the end effector was moved vertically upward to lift the object, and the weight of the object was measured from the value of the tension sensor. After that, impedance control was re-enabled, and the operator carried the object to the target position by applying force directly to the end effector with one hand, and positioned it. Next, impedance control was disabled again, and the object was moved vertically downward to ground the object. Thereafter, the same procedure was used to return the end effector to its original position. It was confirmed that it was able to smoothly transport and position the object of a weight that would not normally be transported by one operator's one hand by using the developed system.

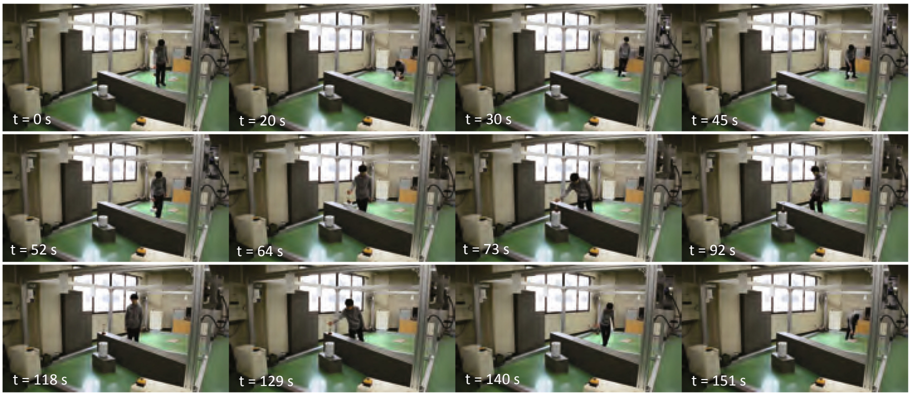


Fig. 4. Object transportation and positioning.

Furthermore, Fig. 5 shows the operator intentionally pushing the object toward the workspace boundary. It can be seen that the object is pushed back into the workspace when the operator releases his/her hand. This is useful as a safety function to prevent the operator from inadvertently pushing an object out of the workspace. Using this method, it is also possible to avoid obstacles during operation by installing a potential field appropriately near obstacles.

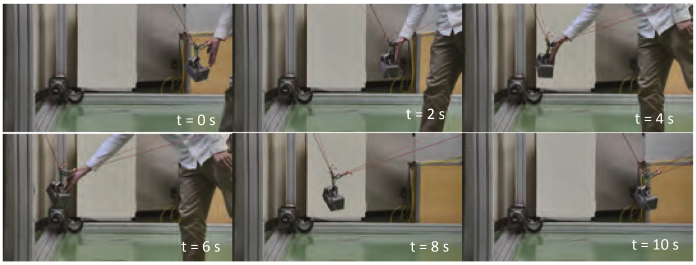


Fig. 5. Avoidance motion.

5 Conclusions and Future Work

In this paper, the development of a suspended CDPR for object transportation and positioning with a long-term objective of application on construction sites was presented. The design is based on a three degrees-of-freedom suspended CDPR that controls the position of an object by hanging with four cables. By the impedance control using cable tension sensors, intuitive transportation and positioning by the operator directly applying force to the object were achieved. Furthermore, by extending this control, workspace departure avoidance control was also introduced.

Authors' future work before on-site application includes the performance evaluation using external measurement devices, the vibration suppression control and automatic generation of potential field with obstacle detection.

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