

# CubiX: Portable Wire-Driven Parallel Robot Connecting to and Utilizing the Environment

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**Abstract**—A wire-driven parallel robot is a type of robotic system where multiple wires are used to control the movement of an end-effector. The wires are attached to the end-effector and anchored to fixed points on external structures. This configuration allows for the separation of actuators and end-effectors, enabling lightweight and simplified movable parts in the robot. However, its range of motion remains confined within the space formed by the wires, limiting the wire-driven capability to only within the pre-designed operational range. Here, in this study, we develop a wire-driven robot, CubiX, capable of connecting to and utilizing the environment. CubiX connects itself to the environment using up to 8 wires and drives itself by winding these wires. By integrating actuators for winding the wires into CubiX, a portable wire-driven parallel robot is realized without limitations on its workspace. Consequently, the robot can form parallel wire-driven structures by connecting wires to the environment at any operational location.

## I. INTRODUCTION

Wire-driven robots, capable of handling strong forces up to the wire breaking strength with high degrees of freedom provided by multiple wires, have been developed extensively [1]–[12].

Cable-driven parallel robots (CDPR) consist of a movable end effector, an external frame, and wires connecting them. The end effector is driven by actuators fixed to the external frame, which wind the wires connecting the frame and the end effector. The separation of actuators and end-effectors enables the lightweight and simplification of the movable part. In CoGiRo [1], a CDPR, a box-shaped end effector with a robot arm is connected to the external frame via wires, enabling the robot arm to move in 3-dimensional space by winding the wires. Similarly, CableRobot simulator [2], also a CDPR, is a rideable device capable of moving a human-occupied end effector in space at accelerations of up to 1.5 G, offering immersive experiences for driving simulations. Such configurations, where the end effector is connected to the external frame via wires and driven through wire actuation, are prevalent. Similar configurations include the ultra-high-speed wire-driven robot FALCON [3], capable of achieving accelerations of up to 43 G, as well as IPAnema [4], a CDPR developed for industrial use. Another example is SkyCam [5], deployed in sports stadiums to move cameras around the playing field. All these systems control the posture of the end effector using force transmission through multiple wires. However, the actuators generating the force are fixed



Fig. 1. The overview of CubiX connecting to and utilizing the environment.

to the external frame surrounding the end effector, limiting the robot's operational range within this frame.

In contrast, there are studies that enable the movement of the entire frame of CDPR by employing multiple carts equipped with wire-winding modules [6]–[8]. However, as a result, the robot's operational range is confined to the plane where the carts carrying the wire modules can move. Marionet-CRANE [9], [10], another CDPR, consists of a series of cranes with wire modules attached, requiring humans to install as many cranes as wires used in the operating area, which does not necessarily free the CDPR from its external frame limitations.

Turning our attention to robots that utilize the environment through wires, recent studies have explored improving vehicle mobility by connecting a wire from the vehicle to the environment via drones [11], and enhancing humanoid capabilities through wire-connected carabiners, allowing the reinforcement of forces exerted by the humanoid [12]. While wire-driven mechanisms in these studies were confined to

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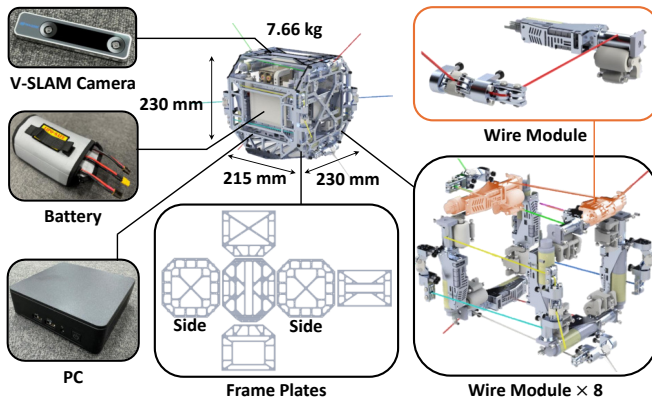


Fig. 2. The hardware structure of CubiX. It has 8 wire modules, and its cube-shaped structure consists of 6 frame plates. It is also equipped with devices such as a PC, battery, and camera necessary for operation.

linear force assistance, utilizing the environment through wires is considered one effective option for wire-driven robots.

Therefore, in this study, we develop CubiX (shown in Fig. 1), a wire-driven robot equipped with actuators capable of winding wires internally. CubiX connects multiple wires extending from its body to the environment and drives itself by winding these wires. Through this approach, robots can form parallel wire-driven structures tailored to specific tasks by utilizing the environment at their operational sites.

## II. DESIGN OF CUBIX

### A. Design of the Overall Structure

The overall structure of CubiX and its hardware configuration are shown in Fig. 2.

Wire-driven force can only be generated by winding wires, and due to the property that unwinding wires does not produce force, the dimension controllable by  $m$  wires is  $m - 1$  dimensional. To control a 6-dimensional wrench combining 3-dimensional translational forces and 3-dimensional torques, at least 7 wires are needed to generate driving force. Considering CubiX's movement in 3-dimensional space, it is desirable for CubiX to exert force in all directions from its central body, thus requiring wires to be extended from CubiX in all directions. Therefore, by also considering symmetry, a total of 8 wire modules are installed.

As shown in the lower right of Fig. 2, the 8 wire modules are arranged along the edges of the cube. The wire path starts from the winches for winding the wire, passes through wire relay points located on opposite edges, and exits CubiX's body. This arrangement allows for a longer distance between the winch and the wire relay point, reducing the fleet angle [13]. Moreover, since the wires only pass on the faces of the cube, batteries, circuit components, and a PC can be installed inside CubiX without interference from wires.

As shown in the lower center of Fig. 2, CubiX's cubic structure is composed of 6 frame plates. 4 wire modules are mounted on each of the 2 side frame plates, and these 2 side frame plates are connected by the 4 middle frame plates. Each frame plate has grooves, allowing the plates to interlock when assembling the cubic structure, thereby increasing its strength.

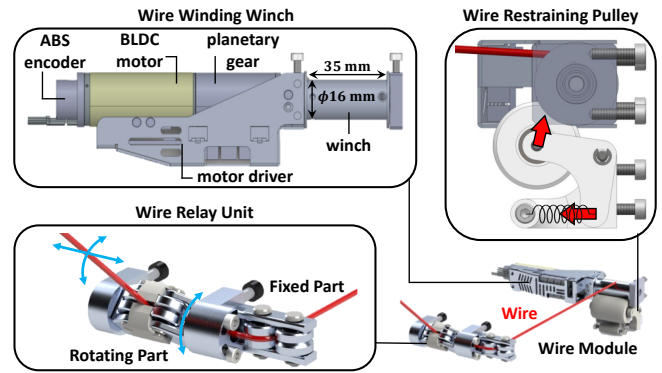


Fig. 3. The overall structure of the wire module. It consists of 3 elements, the wire winding winch, the wire restraining pulley, and the wire relay unit.

### B. Design of the Wire Module

The overall view and individual components of the wire module of CubiX are shown in Fig. 3. The wire module is comprised of three elements: the wire winding winch, the wire restraining pulley, and the wire relay unit, designed to wind the wires connected to the environment and generate tension.

The wire winding winch, shown in the upper left of Fig. 3, winds the wire by rotating the winch connected to a motor. Since CubiX incorporates a total of 8 wire modules, each wire winding winch is required to be lightweight and compact. Taking note of Musashi, a musculoskeletal humanoid equipped with 74 modules called muscle modules, comprising a wire winding mechanism, motor, gear reducer, tension sensor, motor driver, and IMU [14], we referenced this design for the wire winding winch of CubiX. These winches feature a torque constant of 14 mNm/A, a reduction ratio of 53:1 with a planetary gear head, and dimensions of 16 mm in diameter and 35 mm in length, achieving the performance parameters outlined in Table I.

TABLE I  
PERFORMANCE OF THE WIRE WINDING WINCH

Parameter	Value
Maximum Continuous Tension	180 N
Wire Winding Speed	242 mm/s
Wire Winding Length	5.3 m

The wires used are Vectran®, high-performance ropes with a diameter of approximately 1.0 mm and a breaking strength of 1000 N.

The wire restraining pulley, shown in the upper right of Fig. 3, prevents irregular wire winding while the wire is being wound. To wind up a long wire, multiple layers of wire are wound around the wire winding winch. The wire restraining pulley, pressed against the wire winding winch by tension springs, prevents the wire from changing direction before the wire reaches the edge of the winding winch. Additionally, by smoothing the end face of the wire restraining pulley to the diameter of the wire, the direction of winding is encouraged to switch when the wire reaches the end of the winding winch. Moreover, it prevents the wire from detaching from the wire winding winch when not under tension.

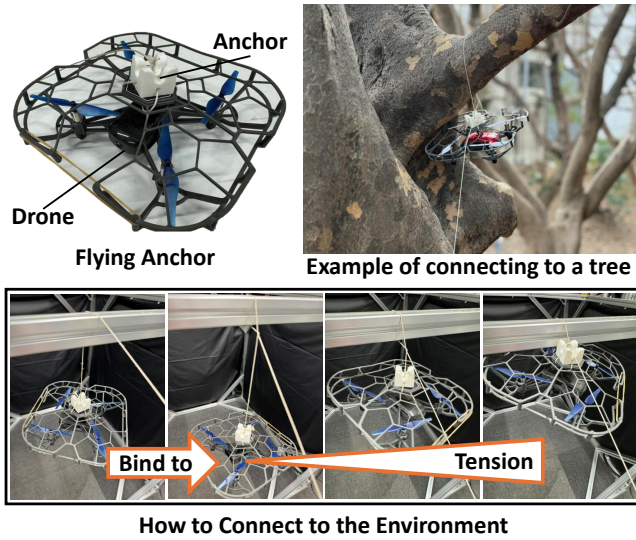


Fig. 4. The overall structure of the flying anchor. The drone with the anchor circles around a pillar, looping the wire around it, and then CubiX applies tension to anchor the wire to the environment.

The wire relay unit, shown in the lower left of Fig. 3, aligns wires connected to the environment and transfers them to the wire winding winch. Inspired by the wire-interference-driven robotic arm SAQIEL [15], which developed a mechanism for transferring wires between arbitrary points, we used a similar mechanism in the wire relay unit of CubiX. Wires connected to the environment are transferred through the wire relay unit to the wire winding winch. At this time, the rotational part of the wire relay unit rotates according to the direction of the wires connected to the environment. Thus, regardless of the orientation of the wire connection, the wire is aligned and transferred to the wire winding winch. Consequently, regardless of CubiX's orientation, wires connected to the environment are transferred in an aligned state to the wire winding winch.

### C. Electrical Configuration

The devices installed in CubiX are listed in Table II.

TABLE II  
DEVICES INSTALLED INTO CUBIX

Device	Description	Quantity
PC	Intel NUC 12 Pro Mini PC Kit	1
Wireless Emergency Stop Receiver	Harmony ZBRR4	1
Power Relay	OMRON G9EA-1-B DC24	1
Camera	Intel RealSense Tracking Camera T265	1
Logic Battery	HRB 3S 6000mAh 11.1V	1
Power Battery	HRB 6S 3300mAh 22.2V	2

CubiX is required to operate autonomously; therefore, devices necessary for operation such as PC, battery, and sensors are installed inside its body. The interior of CubiX is divided into three tiers using sheet metal parts: the lower tier houses the PC, the middle tier contains the battery, and the upper tier accommodates other circuit devices including the V-SLAM camera. The battery voltage is 12V for the logic system and 48V for the power system.

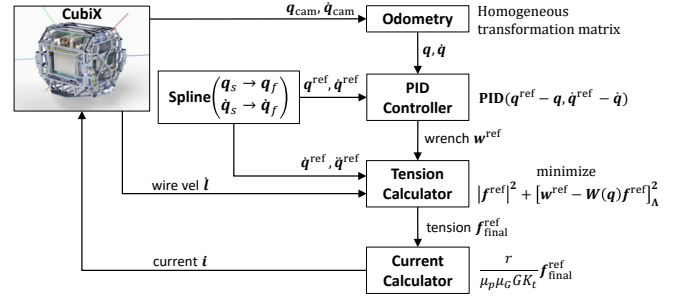


Fig. 5. Pose control loop to move the pose of CubiX to the target pose. Calculate the tension required for each wire to follow the spline path.

### D. Flying Anchor to Connect Wires to Environment

There are various means to connect wires to the environment, such as manual tying by human hands, using carabiners for connection, or throwing hooks to attach to objects. As an example of these methods, we present a flying anchor using a drone, as shown in Fig. 4. The drone winds the wire around objects like pillars or trees in the environment and secures the wound wire to the environment using the anchor.

For instance, when connecting the wire to a pillar, as shown in the 4 images in Fig. 4, the drone at the end of the wire circles around the pillar to tie the wire. By applying tension to the wire in this state, the anchor attaches to the wire tied to the pillar, securing the wire to the environment. To undo this, loosening the tension releases the anchor from the knot using the drone's weight. At this point, with the anchor attached to the top center of the drone, the drone's posture becomes horizontal in mid-air, allowing it to fly again to untie the wire. The anchor, despite its lightweight at 5 g, has been confirmed to withstand a load of up to 35 kg. Additionally, a lightweight and compact drone, Tello EDU, was used for this purpose.

## III. CONTROLLER OF CUBIX

### A. Pose Control of Wire-driven Floating Link

CubiX is considered as a wire-driven floating link connected to the environment via a free joint, allowing it to move in 3-dimensional space. The pose control loop of CubiX is shown in Fig. 5.

In the Odometry block of Fig. 5, the pose  $q_{cam}$  and velocity  $\dot{q}_{cam}$  estimated by the Intel RealSense Tracking Camera T265 using visual SLAM are transformed into the coordinates of CubiX's center, yielding  $q$  and  $\dot{q}$ .

In the Spline block of Fig. 5, a 3rd-order spline path is computed to reach the specified final pose and velocity  $q_f$ ,  $\dot{q}_f$  from the initial pose and velocity  $q_s$ ,  $\dot{q}_s$  within a designated time. This results in obtaining the target pose  $q^{ref}$ , target velocity  $\dot{q}^{ref}$ , and target acceleration  $\ddot{q}^{ref}$ .

In the PID Controller block of Fig. 5, a PID control is performed to adjust  $q$ ,  $\dot{q}$  to match  $q^{ref}$ ,  $\dot{q}^{ref}$ , resulting in the feedback wrench  $w_{fb}$ . Additionally, the gravity compensation wrench  $w_g$  calculated by Pinocchio [16], the dynamics computation library, is added as a feedforward wrench to obtain the desired wrench  $w^{ref}$ .

Next, in the Tension Calculator block of Fig. 5,  $w^{ref}$  is converted into the tension  $f^{ref}$  that each wire should exert.

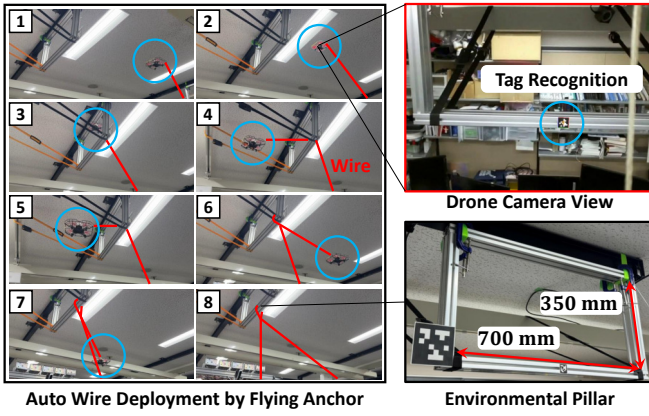


Fig. 6. System of wire deployment using the flying anchor. The relative pose of the flying anchor and the pillar is estimated using tag recognition, and the wire is connected to the pillar following the given path.

The total number of wires is denoted as  $m$ , with  $i \in 1, \dots, m$ . The position where the  $i$ -th wire exits from CubiX, as viewed from the CubiX origin, is denoted by  $r_i$ , and the unit vector pointing from its outlet toward the environment is denoted by  $s_i$ . In this context, using the  $6 \times m$  Jacobian matrix  $\mathbf{W}(\mathbf{q})$ , the wrench  $\mathbf{w}$  exerted by the tension  $\mathbf{f}$  is expressed as shown in Eq. 1. Here, the tension  $\mathbf{f}$  consists of the  $i$ -th wire tension  $f_i$ , where  $\mathbf{f} = [f_1, \dots, f_m]^\top$ , and the tensile direction is considered positive.

$$\mathbf{w} = \mathbf{W}(\mathbf{q})\mathbf{f}, \text{ where } \mathbf{W}(\mathbf{q}) = \begin{bmatrix} s_1 & \dots & s_m \\ r_1 \times s_1 & \dots & r_m \times s_m \end{bmatrix} \quad (1)$$

Based on this, a tension-based joint-space controller, which has been studied for musculoskeletal humanoid control [17], is referenced to determine the tension  $\mathbf{f}^{\text{ref}}$  exerting the desired wrench  $\mathbf{w}^{\text{ref}}$  by solving the quadratic programming problem in Eq. 2. Here,  $\Lambda$  denotes the weight matrix, and  $\mathbf{f}^{\text{min}}$ ,  $\mathbf{f}^{\text{max}}$  represent the vectors of minimum and maximum wire tensions.

$$\begin{aligned} \min_{\mathbf{f}^{\text{ref}}} & \quad \|\mathbf{f}^{\text{ref}}\|^2 + \left[ \mathbf{w}^{\text{ref}} - \mathbf{W}(\mathbf{q})\mathbf{f}^{\text{ref}} \right]^\top \Lambda \left[ \mathbf{w}^{\text{ref}} - \mathbf{W}(\mathbf{q})\mathbf{f}^{\text{ref}} \right] \\ \text{s.t.} & \quad \mathbf{f}^{\text{min}} \leq \mathbf{f}^{\text{ref}} \leq \mathbf{f}^{\text{max}} \end{aligned} \quad (2)$$

In addition, compensatory tensions are computed to offset wire winding winch inertia torque and shaft friction loss torque. These tensions are added to  $\mathbf{f}^{\text{ref}}$  to obtain  $\mathbf{f}_{\text{final}}^{\text{ref}}$ . These computations rely on acceleration  $\ddot{\mathbf{q}}^{\text{ref}}$  and wire velocity  $\dot{\mathbf{l}}$ .

Finally, in the Current Calculator block of Fig. 5, the current  $i$  commanded to each motor is obtained by scaling  $\mathbf{f}_{\text{final}}^{\text{ref}}$  according to Eq. 3, where  $r$  is the wire winding winch radius,  $\mu_p$  is the pulley transmission efficiency,  $\mu_G$  is the gearhead transmission efficiency,  $G$  is the reduction gear ratio, and  $K_t$  is the torque constant.

$$i = \frac{r}{\mu_p \mu_G G K_t} \mathbf{f}_{\text{final}}^{\text{ref}} \quad (3)$$

Thus, wire tension-based pose control is achieved to enable CubiX to follow its path.

## B. Wire Deployment with Flying Anchor

The wire deployment control using the Flying Anchor is shown in Fig. 6. In this setup, wires are arranged on pillars fixed to the ceiling, each measuring  $350 \text{ mm} \times 700 \text{ mm}$ . The relative pose of the pillars is estimated using the AprilTag [18] attached to the pillars and visual odometry executed internally by the drone. By following specified paths, the wires are fastened to the pillars. The drone communicates with the PC mounted on CubiX via Wi-Fi, through which it transmits images and visual odometry results to the PC and receives target velocity vectors as control commands. On CubiX's PC, image-based pose estimation using the AprilTag and PID control of the drone for tracking the target pose are performed.

## IV. EXPERIMENTS

### A. Spatial Movement Driven by 8 Wires

In this experiment, CubiX is driven by the maximum number of wires it can wind, which is 8 wires, to perform spatial movements. The aim is to evaluate whether the design and control of CubiX function correctly as a wire-driven robot. A frame measuring  $1 \text{ m} \times 1 \text{ m} \times 1 \text{ m}$  is prepared as the environment, with 8 wires evenly distributed in all directions. CubiX's operation and wire placement are shown in Fig. 7, and the time-series data of  $\mathbf{q}$ ,  $\mathbf{q}^{\text{ref}}$  are shown in Fig. 8. Using the hook attached to CubiX, it lifted a 1.0 kg box to a platform 0.45 m above.

From Fig. 7, it is evident that CubiX successfully lifted and placed the box onto the platform during spatial movement. Furthermore, from Fig. 8, it can be observed that CubiX tracked the target position and orientation without exhibiting significant oscillations, except for the portions indicated by the red circle. This experiment demonstrated that CubiX, equipped with a total of 8 wire modules and connected wires to the environment, can follow its intended path by calculating and winding the necessary tensions of these wires.

However, the error from the target occurred during the specific interval indicated by the red circle. Observing the corresponding part marked with a green circle in the graph of  $\mathbf{f}_{\text{final}}^{\text{ref}}$  in Fig. 8, it can be seen that 2 wires hit their  $\mathbf{f}^{\text{max}}$ . This indicates that the Jacobian matrix  $\mathbf{W}(\mathbf{q})$  at this pose of CubiX is unable to represent the target wrench. When the feasible wrench is biased in one direction, the optimization in Eq. 2 may fail to solve, leading to instability if feedback wrenches are demanded in directions difficult to exert. To address this issue, adjusting the optimization weights  $\Lambda$  or designing the wire placement with large wrenches in all directions could be considered.

### B. Outdoor Experiment

In this experiment, CubiX was taken outdoors to demonstrate wire-driven movement by connecting wires to trees, showcasing CubiX as a portable CDPR. Two wires were placed on each of the trees on either side of CubiX, totaling 4 wires, to perform spatial movement. The operation of CubiX is shown in Fig. 9, and the time-series data of  $\mathbf{q}$  is shown in

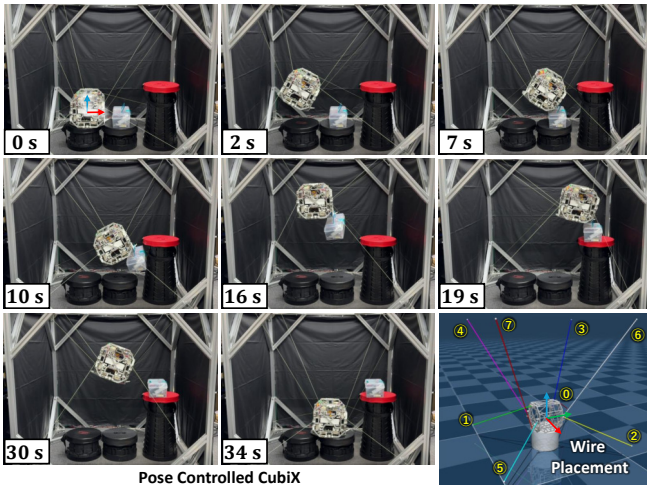


Fig. 7. Pose controlled CubiX and the wire placement. CubiX correctly followed the given path and transported the box onto the platform.

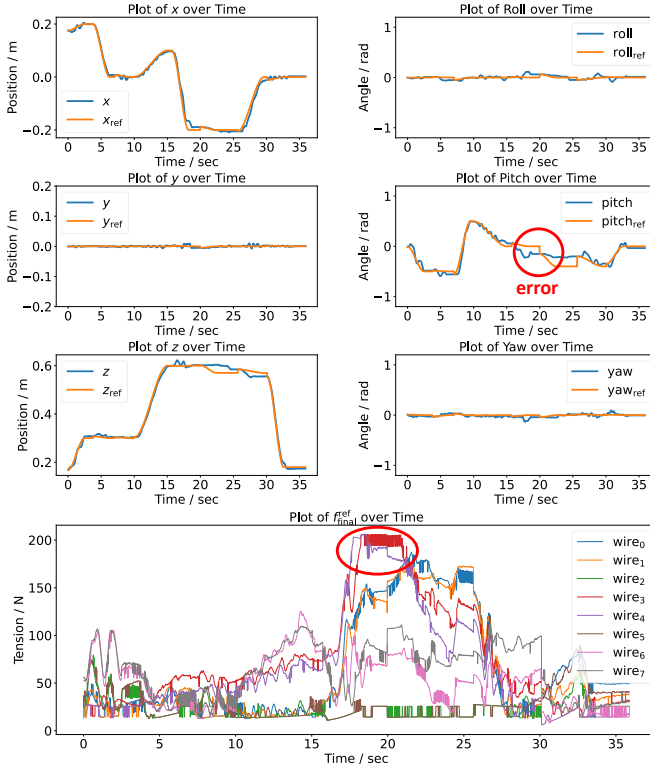


Fig. 8.  $q$ ,  $q^{\text{ref}}$  and  $f^{\text{ref}}$  in 8-wire drive experiment. These results show that the current pose of CubiX followed the target pose, except for the area indicated by the red circle.

Fig. 10. CubiX was driven by commanding target tensions directly to each wire.

In Fig. 10, focusing on the  $y$ -direction, it is observed to increase from  $-0.5$  m to  $0.5$  m, indicating CubiX's movement from the left tree to the right tree. The fact that CubiX was able to connect itself to the environment via wires and drive by winding them up in outdoor location demonstrates that the developed CubiX is a portable CDPR integrated with the necessary devices such as actuators, PC, battery, and sensor for operation. Furthermore, CubiX in this experiment is driven by 4 wires, resulting in an underactuated system since CubiX has six degrees of freedom. However, it successfully accomplishes the movement from the left tree to the right

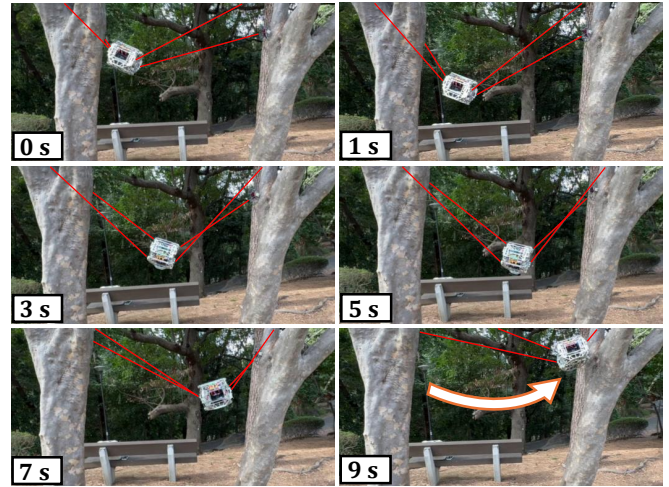


Fig. 9. CubiX in outdoor experiment. CubiX is connected to the environment by 4 wires, 2 on each side of the tree. It shows that CubiX has moved from the tree on the left to the tree on the right.

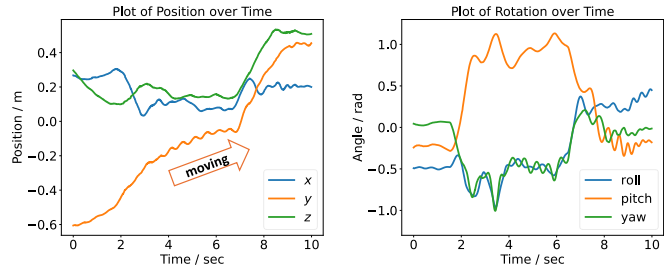


Fig. 10.  $q$  in outdoor experiment. The increase in the  $y$  direction from  $-0.5$  m to  $0.5$  m indicates that CubiX is moving from tree to tree.

one. This indicates that by altering the wire placement or the number of wires, parallel wire-driven structures can be formed to match the environment in which CubiX connects and uses.

### C. Wire Deployment by Flying Anchors

In this experiment, 2 flying anchors were used to connect CubiX's wires to the environment, followed by CubiX's spatial movement, demonstrating CubiX's ability to autonomously connect wires to the environment and drive itself using them. Following the method outlined in Subsection III-B, CubiX was driven by directly commanding tension after connecting the wires to 2 pillars on the ceiling using the flying anchors. The operation of the 2 flying anchors and CubiX is shown in Fig. 11, while their trajectories are shown in Fig. 12.

From Fig. 12, it is evident that the 2 flying anchors maneuver through the pillars, adjust their pose using AprilTags, and connect the wires to the pillars by circumnavigating them. Additionally, it can be observed that CubiX moves vertically and horizontally using these wires. This outcome demonstrates that CubiX, a portable wire-driven parallel robot, can autonomously connect wires to the environment using flying anchors and drive itself using them.

## V. CONCLUSION

In this study, we developed CubiX, a wire-driven robot connecting to and utilizing the environment, and conducted experiments involving spatial movement with 8-wire drive,

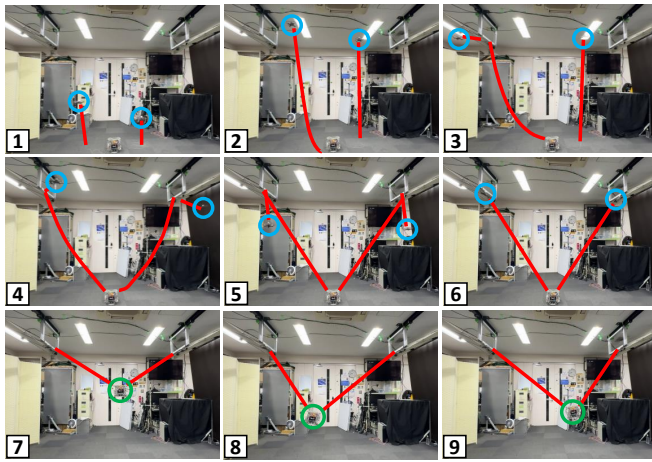


Fig. 11. CubiX and 2 flying anchors in wire deployment experiment. It shows that wires were connected to pillars in the environment by flying anchors and that CubiX was able to be driven by these wires.

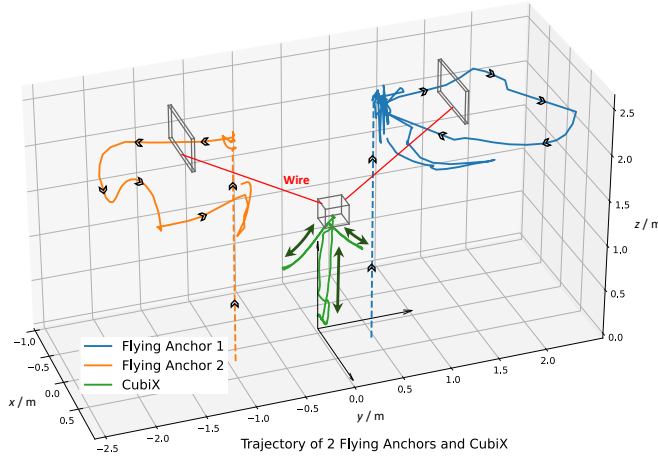


Fig. 12. Trajectory of 2 flying anchors and CubiX. Until the flying anchor recognizing the AprilTag, its trajectory is indicated by dashed lines. It shows that the wires were connected to the pillars by 2 flying anchors circling around the pillars. It also shows that CubiX used those wires to move up and down and left and right.

outdoor parallel wire-drive experiments, and wire deployment experiments using flying anchors. CubiX, a cube-shaped wire-driven robot, is equipped with 8 wire modules capable of continuous tensioning of up to 180 N each, enabling it to autonomously control its pose through wire tension calculations. The spatial movement experiments with 8-wire drive demonstrated CubiX's ability to control its pose by connecting with the environment through wires and using them for driving. The outdoor parallel wire-drive experiments confirmed CubiX's capability to form parallel wire drives as a portable CDPR in outdoor locations. Moreover, the wire deployment experiments with flying anchors showcased CubiX's autonomous ability to connect wires to the environment and utilize them for movement.

As future works, optimizing wire placement tailored to specific tasks and integrating tools such as robotic arms and carts with CubiX could expand its capabilities, enabling CubiX to utilize the environment and exhibit performance unconstrained by its physical structure.

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