Cable-Driven Parallel Robot for Warehouse Monitoring Tasks

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***Abstract*—Present manufacturing processes demand innovative methods for inventory management. Unmanned aerial and ground vehicles (UAVs and UGVs) have been shown to be potential solutions as heightened mobility and wide areas of operation are provided. However, they struggle with battery life, physical restrictions, and highly trained operators. A feasible alternative is offered through cable driven parallel robots. They provide low inertia, high payload-to-weight ratios, and a large operation volume. In order to design any given CDPR system, the static behavior must be understood and is presented. This paper also integrates actuation, camera stabilization mechanisms, and computer vision into a singular CDPR system. Being modular and reconfigurable, this system may quickly and accurately scan storage racks within a warehouse.**

***Index Terms*—cable driven robot, warehouse inventory, skycam**

I. Introduction

As manufacturing processes increase in prevalence, innovations through robotic systems within warehouses become more desired. Currently, issues in inventory management arise due to product diversification, suboptimal selection of products, and inaccurate or incomplete inventory [1]. Previously, unmanned aerial and ground vehicles (UAVs and UGVs) have proven beneficial in inventory management and process automation tasks [2][3][5]. Both UAVs and UGVs provide efficiencies in contrast with human workers, but UGVs encounter restrictions primarily with larger rack heights. UAVs provide heightened mobility, can operate within a wide area, and may prevent injuries workers face when using scissor and fork lifts.

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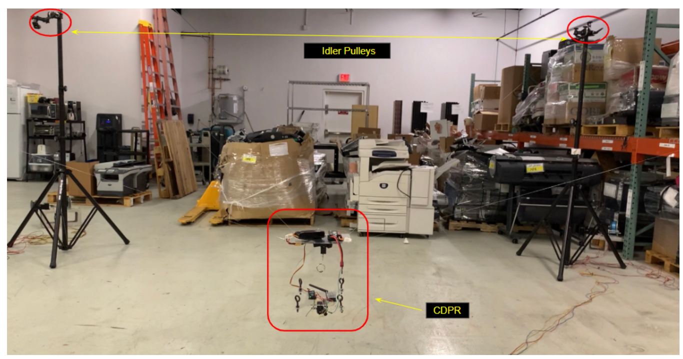

Figure 1: Proposed Cable driven parallel robot system in the tested warehouse

However, the limited battery life, requirement of trained operators, and overall reliability of UAVs suggest alternatives.

Offering similar capabilities to UAVs, cable driven parallel robots (CDPR) appear to be a potential alternative. CDPRs are made by attaching multiple cables to an end effector, typically a small plate. The cables act as replacements to rigid links found in other systems. Movement of CDPRs is generated by actively changing the lengths of the cables. Advantages of these systems include low inertia, modularity and reconfigurability, high payload-to-weight ratios, and large operation volumes [4][7]. Unlike UAVs, the payload is minimized as motors and large battery packs may be excluded from the end effector. Moreover, CDPRs provide capabilities to navigate where UGVs may not. These characteristics foreshadow promise in truck yard, shipyard dock, and warehouse environments. This paper presents a CDPR system to be used for inventory management within a warehouse (Figure 1).

One use case may be explicitly shown by Tesla's Nevada based gigafactory. Tesla's warehouse contains tall double-deep racks that require additional machinery and manpower to access each level. The gigafactory also contains a large truck yard that demands similar procedure (Figure 2). Additionally, CDPRs currently show use in professional sports and entertainment. The most notable CDPR is the ”Skycam[1]” as exclusively used in the National Football League. Through the proposed system, the operator can manage inventory from a remote location and provide 24/7 monitoring of the warehouse. This paper is split into five other sections. Section II describes related works. Section III presents the methodology used and a static analysis of the cables. Section IV describes the technical design for the actuation, stabilization mechanism, and image processing. Section V showcases the warehouse trials and Section VI draws conclusions and discusses future work.

Figure 2: Double-deep rack warehouse structure and truck yard at Tesla’s gigafactory

II. Related Work

As previously mentioned, the use of robotic systems within logistic centers and warehouses is of increased desire. Big supply chain warehouse facilities are susceptible to tall racking structures and injured workers. For inventory processes, UAV’s and UGV’s provide great scanning tools to replace humans in dangerous zones. Chouaib Harik et al. explored a wireless communication camera attached to a UAV to scan inventory in real time and use UGVs as charging hubs in between flights. Optical scanners were attached to both platforms with a manually piloted UAV [5]. Their paper demonstrated how robotic agents can be used to scan bar codes by computer vision techniques.

Previously, adaptive designs for cable-suspended camera systems have been made to enhance performance in mobility. The disruptions within a CDPR remain within the the systems ability to provide equal tension for each cable. Experiments on the performance indices were conducted for elastic stiffness, stiffness magnitude, and dexterity by Abdolshah et al. They describe how dexterity is an important characteristic within parallel cable driven robots and to project their kinematic behavior within a rectangular workspace. Performance analysis of the CDPR showed that increased stiffness is an ideal factor for robustness and mobility [6]. End effector position within the given workspace also displayed changes for dexterity in regards to cable lengths and workspace shape.

Any desired trajectory for a cable suspended camera system depends on the given length of the cables, number of cables, cable tension factor, and workspace shape. Difficulties arise when the workspace is irregular and body twist occurs between the end-effector and attachment points. Zhou et al. discovered that irregular payload shapes were also inconvenient due to the angle of twist created by the attachment system [7]. In order to keep constant cable tension within non-symmetrical loads, Zhou et al. investigated cable attachment choices that best suited the greatest tension factor across the system to enhance transportation. A reconfiguration of the base gantry permitted the most desirable tension factor for a given trajectory.

Furthermore, the number of cables of a CDPR can be changed depending on the task. Narayanan et al. presented a robust outdoor agricultural CDPR that used a trilateration technique for modular purposes. The conceptual design proposed involved an increased payload to the system’s end-effector to manipulate agricultural harvest. Workspace considerations for height restrictions were seen as payload increases were implemented. Data gathered from the CDPR displayed that a three cable system relied on the diameter of the in-circle and was shown that an increase in diameter correlated to height constraints before cables met max tension [8]. Although constraints were found within the system, kinematic modeling proved that the proposed robot met standards for typical outdoor farm conditions.

III. Methodology

Generally, the storage racks of a warehouse cover a large area. It is desired for the CDPR system to completely encapsulate the racking area of the warehouse. This, however, brings a new set of obstacles to overcome. It was found as the operating volume and mass of the end effector increase, so too does the tension in each cable. Consequently, certain locations of the workspace yield immense tension while others minimal tension, generating ”spatial limits” [8]. These limits must be understood for safe and reliable operation to be ensured. In order to avoid over-engineering and gain a better grasp of the underlying physics of the system, force equations were developed and subsequently placed into an augmented matrix to estimate cable tensions. It is important to note that these calculations consider a static case free of accelerations (both linear and angular).

[1]More on the Skycam found here: http://www.skycam.tv/

A. Cable Statics

Figure 3 depicts an arbitrary CDPR quad-cable scheme in Cartesian coordinates. Position vectors $\overrightarrow{rp_i}$ (where i=1, 2, 3, 4) represent the coordinates from the origin to each pulley while the vector $\overrightarrow{ro}$ represents the CDPR's position with respect to the origin. Vector subtraction may then be performed to produce the CDPR's position vectors for each cable with respect to the pulleys $\overrightarrow{r_i}$. The force due to gravity vector pointing downwards may be found as $\overrightarrow{F_g} = \begin{bmatrix} 0 & 0 & -mg \end{bmatrix}$. The force vector for each cable acts in the direction of $\overrightarrow{r_i}$, namely, the unit vector. When the unit vector is multiplied by the force vector's magnitude $|F_{Ti}|$, the force vector for that cable may be produced. It is better shown by, $\overrightarrow{F_{Ti}} = |F_{Ti}| * \hat{r}_i$. A summation of forces presents $\overrightarrow{F_{T1}} + \overrightarrow{F_{T2}} + \overrightarrow{F_{T3}} + \overrightarrow{F_{T4}} + \overrightarrow{F_g} = m\frac{d^2\overrightarrow{ro}}{dt^2}$ where $m\frac{d^2\overrightarrow{ro}}{dt^2} = 0$. All four cables possess x, y, and z force components to provide three equations.

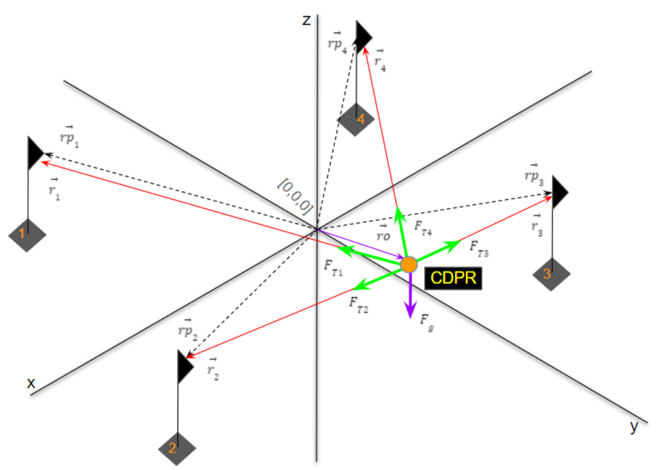

Figure 3: Arbitrary cable workspace with force vectors of each cable

Furthermore, recalling a static assumption, a summation of moments about the origin may be illustrated by $\sum M_o = \left[\overrightarrow{ro} \times \overrightarrow{F_{T1}}\right] + \left[\overrightarrow{ro} \times \overrightarrow{F_{T2}}\right] + \left[\overrightarrow{ro} \times \overrightarrow{F_{T3}}\right] + \left[\overrightarrow{ro} \times \overrightarrow{F_{T4}}\right] = 0$. In order to determine the tensions in a four cable system, the three force equations and one moment equation (focusing on any coordinate $\hat{i}$, $\hat{j}$, or $\hat{k}$) were then placed into an augmented matrix as shown below. As mentioned, the system of equations placed in the augmented matrix may be solved through RREF. This proposed method, allows for tension estimations to be made regarding any cable configuration with any end effector mass. Utilization of the $\hat{i}$ equation would lend A = $\hat{r_1}[3]\overrightarrow{ro}[2] - \hat{r_1}[2]\overrightarrow{ro}[3]$, B = $\hat{r_2}[3]\overrightarrow{ro}[2] - \hat{r_2}[2]\overrightarrow{ro}[3]$, C = $\hat{r_3}[3]\overrightarrow{ro}[2] - \hat{r_3}[2]\overrightarrow{ro}[3]$, and D = $\hat{r_4}[3]\overrightarrow{ro}[2] - \hat{r_4}[2]\overrightarrow{ro}[3]$ to be placed within Equation 1.

$$\begin{bmatrix} \hat{r_1}[1] & \hat{r_2}[1] & \hat{r_3}[1] & \hat{r_4}[1] & ma_x \\ \hat{r_1}[2] & \hat{r_2}[2] & \hat{r_3}[2] & \hat{r_4}[2] & ma_y \\ \hat{r_1}[3] & \hat{r_2}[3] & \hat{r_3}[3] & \hat{r_4}[3] & m[a_z + g] \\ A & B & C & D & mg\overrightarrow{ro}[2] \end{bmatrix} \quad (1)$$

Innately, in order for CDPRs to operate, all cables must also experience positive tension [8]. Upon testing various configurations one may notice that the safe operating space of the CDPR is a fraction of the entire space. Specifically, as the CDPR increases in the z-axis, nears an edge, or nears a corner, tension simultaneously increases. In fact, the closer the CDPR moves to the height of the operating volume (2.43 m or 8 feet for this paper), the nearer it gets to a singularity. Figure 4 represents tension in all cables as result of origin centering. It is also shown that the end effector's height resembles an exponential relationship with tension values in the cables. Moreover, changes in tension become more significant with smaller changes in height as the maximum is approached.

This behavior allowed an appropriate motor to be selected based on the desired work space.

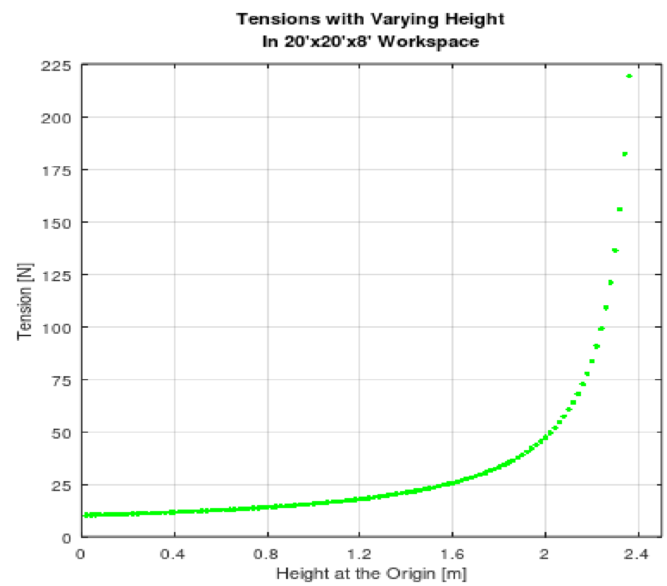

Figure 4: Tension vs. Height at the origin in all cables

IV. Technical Design

In order for a CDPR to successfully travel and scan inventory within a warehouse, a series of thresholds must be met. The robot must provide modest speed, dynamic stability, and intuitive control. Typical adult walking speeds range between 1.3 and 2.3 m/s (2.9 and 5.1 mph)[9]. However, navigation to higher levels of racking can be a difficult and dangerous task. As a result, inventory processes tend to be cumbersome. Machinery such as electrical or diesel scissor lifts must be introduced. It is also crucial that the camera used for scanning inventory remain parallel with the ground independent of the end effector's location and orientation. Depending on the location of the end effector, the angle of inclination changes. The camera must also come equipped with its own actuator in order to perform panning capabilities for scanning inventory. Figure 5 illustrates a component diagram of the CDPR.

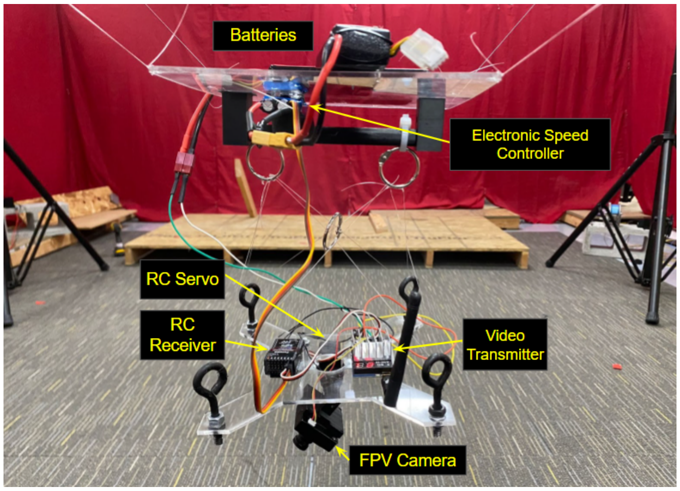

Figure 5: CDPR component diagram

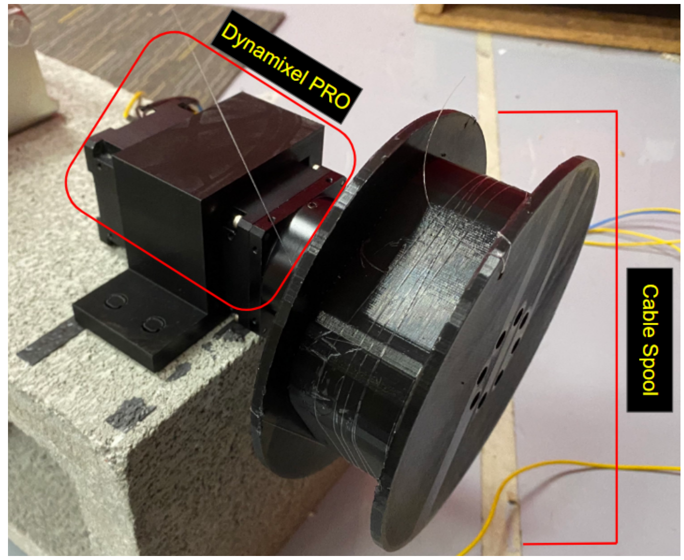

Figure 6: Dynamixel PRO with 150 mm spool mounted to the horn

A. Actuation and Control

A CDPR may be defined by the system's DOF, n, and the number of cables used, m. As previously mentioned, a ground-mounted quad-cable and winch scheme was utilized. This allowed for full dynamic constraint of the system as $n + 1 = m$ [10].

Moreover, the CDPR utilized four ROBOTIS Dynamixel PRO smart actuators[2] (Figure 6; H54-200-S500-R) to move through the operation space. Under no load conditions, the Dynamixels provide up to 33 rpm and 45 Nm of continuous torque. When a load resulting from the end effector and three other cables is experienced, the motors provided roughly 27 rpm. These motors were selected using the max possible tensions estimated in a 20' x 20' x 8' operation space (of which was 345 N near max height close to a corner). Moreover, they provide an excess of torque that may be freely sacrificed for heightened velocity. Increasing the travel radius of the cable by means of enlarging the horn of the Dynamixel, increased the tangential velocity of the cables. For instance, the Dynamixel's standard horn has a 49 mm diameter. A 150 mm diameter cable spool was mounted to the horn of each Dynamixel to achieve a travel velocity of roughly 0.21 m/s (0.45 mph) in any x, y, or z direction (Figure 6).

Controlling of the system was made such that anyone may confidently move the CDPR with minimal practice. Using a Logitech F310 joystick within a Robot Operating System (ROS)[3] framework, the CDPR may be controlled. ROS acts as the communication middleware between the joystick and Dynamixels. Additionally, movement of the payload is caused through various combinations of clockwise and counterclockwise rotations of each motor where each has the same angular velocity. Six buttons are used to move the CDPR. In order to raise the robot in the z-direction, all motors must rotate counterclockwise (vice versa for lowering in z).

[2]Information and specifications for Dynamixel PRO may be found here: https://emanual.robotis.com/docs/en/dxl/pro/h54-200-s500-r/

[3]More on ROS may be found here: https://www.ros.org/

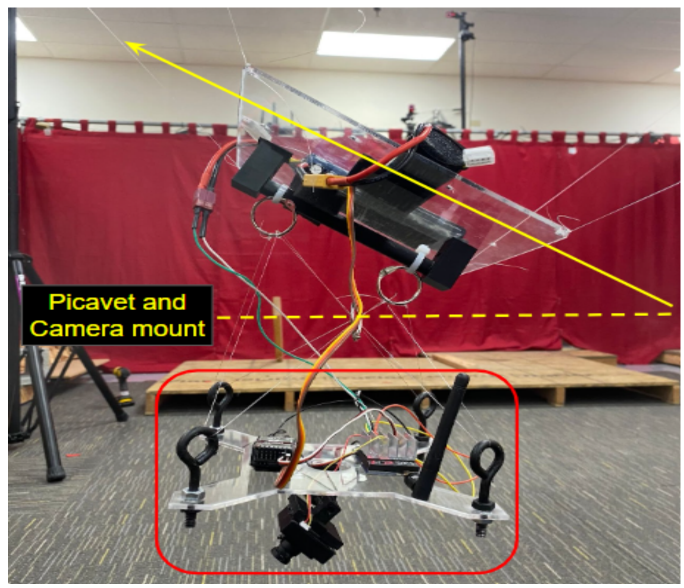

Figure 7: Picavet passively maintaining CDPR's level plane independent of the end effector orientation

B. End-effector Stabilization

It is possible for the camera to be directly mounted upon the end effector, however, changes in orientation are of particular concern. The scanning of inventory becomes increasingly difficult as the camera is not parallel with the ground plane. Specifically in locations nearer to the edges of the operating volume, the angle of the end effector drastically increases. At these positions, scanning becomes nearly impossible. Rapid changes in direction and the completion of a movement also generate oscillations in the end effector requiring further stabilization.

To minimize this, a suspension mechanism previously used

Figure 8: CDPR traveling through the warehouse, moving inline with storage racks, and scanning inventory. Top section A shows the CDPR's scanning path and bottom section B shows the camera's POV

in kite aerial photography (KAP) known as a Picavet (pronounced "peekavay") was utilized (Figure 7). If mounted to the Picavet, the camera may be passively stabilized and a level frame ensured. The Picavet, constructed in an "x" shape, possesses four eye bolts and three rings of which a single thread loops. The center loop both helps prevent the Picavet from twisting and constraining the two most central crossing lines. If oriented at an intersecting angle with the ground, the Picavet will also maintain that position as the CDPR moves[11]. Unlike a gimbal, additional actuation is not required for level plane assurance. Adding components works as a domino effect in this case. The more components that exist on the system, the more mass it has. In turn, the tension in the cables increases which simultaneously raises the required torque from the motors.

C. Inventory Scanning

Many warehouses contain aisles with a double-deep racking structure. Having the ability to pan the camera's field of view is a necessity to successful scan QR codes on either side of the aisle. This also gives the remote operator a sense of awareness while directing the lens anywhere within 180°.

Mounted to the underside of the Picavet is a 5.8 GHz FPV camera. The camera allows for wireless communication via transmitter to a ground-based receiver. The receiver sends the cameras live field of view to be filter for barcode detection 1 frame per millisecond. By using OpenCV, the program is then able create a red bounding box around the decoded QR-code.The program allows for one QR-code to be detected if multiple are within frame. The camera's DOF is provided with a mounted Futaba RS303MR servo to capture a desired area. The servo is connected to a Futaba 2.4 HGz reviever that will allow for radio control by transmitter.

V. Warehouse Experiments

Experiments were conducted with the CDPR in a 20' x 20' x 8' configuration within a warehouse[4]. To begin experiments, the CDPR is calibrated by positioning the end effector and picavet in the center of the workspace. This is to ensure positive tension in each cable free of slack. Using the Logitech F310 joystick, the end effector was then moved in the direction of desired scanning. In order to demonstrate the CDPRs multilevel mobility, it was then raised to the height of products to be detected. Using the transmitter, the camera was then panned 90°. A single lateral motion was then performed to scan multiple packages. The speed of the CDPR allowed each package to be scanned and prevented overshoot of the destination. As QR codes appeared in the camera's field of view, the QR code data was then labeled and processed. As previously stated, a red boundary box was marked around the QR code to show positive detection and for clear indication. Text corresponding to each package is then displayed to the operator and the experiment concluded (Figure 8).

VI. Conclusion and Future Work

This paper proposes the usage of CDPR's within warehouse environments to decrease work related injuries and streamline inventory processes. Although, the presented CDPR was able to reliably navigate and scan inventory within a warehouse, further modifications may be made. As a result of the system's

[4]The authors invite the interested reader to watch a real-time video here: https://www.youtube.com/watch?v=9SmXYqIyNSs

minimal inertia, the end effector demonstrated a tendency to oscillate or sway at the end of its path. A dynamic analysis of the system must be made to better acknowledge the accelerations and impulses encountered. This, in combination with the use of a control algorithm, may improve the systems stability and eliminate oscillations. Moreover, spacial acuity is required as it is expected for the CDPR to be operated from a remote location. Augmenting the picavet with a second motor to provide the camera another DOF for tilting movements in tandem with a visual interface of the workspace may lend for enhanced teleoperation. Such modifications aim to alleviate the struggles of inventory monitoring tasks in warehouses and other large environments where CDPRs' mobility may benefit.

VII. Acknowledgement

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