Winch-Integrated Cable Force Measurement and Verification on Driven Cable Parallel Robot 6 D.o.F

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***Abstract*—A parallel robot was controlled by a cable that manipulated the end effector in the workspace. The force sensor was used to measure cable force, is placed near the drum. From there, the controller computes and executes the necessary control commands. The purpose of this work is to concentrate on string tension modeling and frictional compensation. The cable tension should be adjusted within the desired range, according to the tension measurements given on the winch's pulley side, to avoid sagging cable. The accuracy of the force measured at the force sensor is influenced by the pulley system. Simulate the Dahl model and the Coulomb model, from which you select the appropriate model to compensate for friction. This friction-compensated model shows a 65% improvement in string tension accuracy compared to the uncompensated force.**

***Index Terms*—cable robot, Dahl model, 6 dof, CDPR, tension force, friction, cable force**

I. Introduction

A parallel robot is a structure made up of multiple closed dynamic chains connected in parallel by axes and end-actuators. In terms of impact speed, precision, load, and stiffness, parallel robots surpass serial operations.. In terms of practical use, studies reveal that surgical robots and pick-and-place robots are two common industrial production applications. Stewart Platform movements allow relative motions between the tool and the workpiece in machining applications, with comparable forming performance[3]. Cable-mechanical structures are characterized by a movable base that is connected to the cable through a fixed frame. The cables are fixed to the frame and are wound by spools, which are pulled by the motor to generate force and torque. At the same time, we determine the position of the working head through the length of the cable. The Fox robot is a parallel device that uses cables as links. Each cable is an independent chain with 1 dof. Cable-operated cable robots have advantages over rigid joints because they allow the system to move flexibly thanks to its reduced mass and lower cost. Besides, the travel of the joints is not as limited as the other joints. conventional structure because the cable can be stretched to the desired length thanks to the reel system.

In this study, a cable robot has 6 degrees of freedom controlled by 8 cables shown in Fig. 1. The sensor-controlled integrated mechanical module for high tension measurement and control robot flexibility. Since the musculoskeletal robot is made up of actuators, the ability of the motor actuator has a significant impact on the robot's performance. Tension measurement must be accurate as it affects the direct control of the robot. It is desirable to be a low-friction mechanism because the cable tension is affected by the friction between the structure and the conductor. The force sensor was built into the transmission system to measure the force on the cable without having to place the sensor on the cable. A force sensor is placed at the end of the cable to measure cable strain to prevent overstretching and cable breaking. Besides, measuring the tension of the cable to give feedback to the system to give a command to control the cable to maintain the tension to limit gravitational sagging of the cable. The transmission system consists of pulleys to create additional forces such as inertia or friction, and a cable robot. The cable is guided by three pulleys, one of which is attracted by a force sensor. The mathematical model used to compute cable tension is impacted by this. The friction model is used in this work to increase the accuracy of cable tension measurements (Fig. 2). Friction modeling is used in a variety of robotics applications. For example, in humanoid robots, the upper limb is frequently cable actuated, and the load cell is located within the system. Tension measurement must be precise since it impacts the robot's direct control, which has a substantial impact on its performance. Because friction between the structure and the conductor affects cable tension, it is ideal to have a low-friction mechanism. Pulleys are used to implement these systems. Discrete parts having friction losses, for instance, are employed in a cable-conduit system for surgical robots[5]. The viscous and dry friction coefficients are used in the calculated torque control technique for a cable robot[6]. The reel friction in the cable-driven movement interface was modeled using the Dahl model[7].

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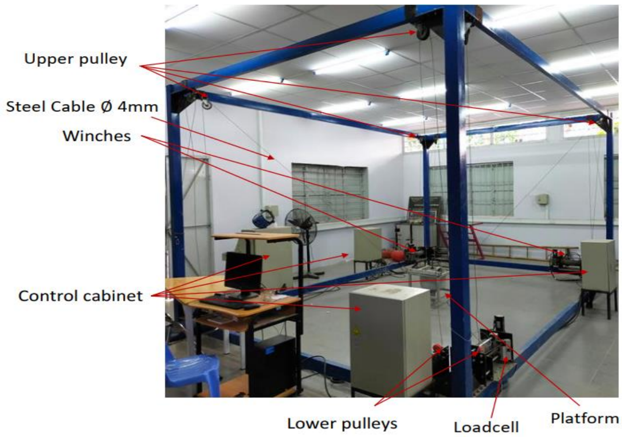

Figure 1. Cable robot in construction with 8 cables ,6 dof

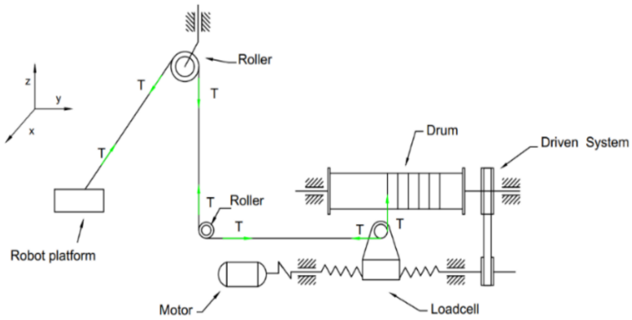

Figure 2. Schematic of cable winch

An end-effector, cables attached to a winch, and pulleys are all common components of CDPRs. Winch and pulley bearing friction, on the other hand, have a detrimental effect on the end effector. This makes precise control impossible. Each cable is guided by pulleys in CDPRs that require high position precision, however, the significant error is caused by pulley bearing friction from cable tension. Because certain components' behaviors are ambiguous, pulley bearing friction has been measured and compensated. Load cell and pulleys are utilized to monitor tension and established experimentally that friction is the most important element determining tension. We suggested an algorithm to compensate for friction by using Dahl model. The accuracy of the Driven Cable Parallel Robot 6 D.o.F. was greatly impacted by model Coulomb friction. Because the cable tension is mostly affected by the dynamic friction of pulleys, these dynamic features are critical to creating highly accurate models such as control and workspace determination. In a static equilibrium, a kinematic Coulomb model correctly predicted the tension by utilizing the relationship between tension and pulley bearing friction. [14] However, in a dynamic state, the pulley bearing friction cannot be represented simply in terms of Coulomb friction. In practical systems, the non-linearity of quick transitions that occur when direction changes have an impact on the micro-displacement (pre-sliding) ranges of friction. And it has a considerable negative influence on the accuracy of the CDPR system because errors generated by changes in friction in the pre-sliding region accumulate. As a result, the kinematics with Coulomb friction model is insufficient for precise control. The Dahl friction model, for example, necessitates the use of a dynamic representation that compensates for non-linear friction models.

The tension relationship and the Kinetic Coulomb model in static equilibrium are used to precisely measure string tension. However, in the dynamic state, pulley bearing friction is not simply represented by kinetic Coulomb friction; in reality, the motion is exceedingly fast and non-linear. Therefore, the Dahl model is used to represent dynamic friction in the pulley system. Section 2 summarizes the workspace analysis of parallel cable-driven systems, including kinematic and cable force distributions. Section 3 describes how to model the friction between the pulleys and the bearings. The results of the parametrization for all cables were given and debated. Section 4 analysis of the tension in Dahl model in cable. Section 5 concludes with conclusions and recommendations for future work.

II. ANALYSIS OF THE CABLE- DRIVEN PARALLEL WORKSPACE

With CDPR kinematics, you consider the position of the moving platform in relation to the flexibility of the joints (the cable length). The Fig. 3 shows the kinematic structure of a robot in which eight cables are attached to one platform, while A_i and B_i (i = 1,..., n) are two points on the cable that connect to the platform[10]. The inverse kinematics of the cable robot is written as [11].

$$a_i - r - Rb_i = l \tag{1}$$

Where: a_i is the position vector of Ai in the base or frame B; b_i is the position vectors of Bi that correspond to the position vectors; R_i corresponds to the rotation matrix which is the motion platform direction.

The rotation matrix R from frame E to frame B can be obtained as follows:

$$R = R_Z(\varphi)R_Y(\beta)R_x(\alpha) = \begin{bmatrix} c\gamma c\beta & c\gamma c\beta s\alpha - s\gamma c\alpha & c\gamma c\beta s\alpha + s\gamma c\alpha \\ s\gamma c\beta & s\gamma c\beta s\alpha + c\gamma c\alpha & c\gamma c\beta s\alpha - c\gamma c\alpha \\ -s\beta & c\beta s\gamma & c\beta c\alpha \end{bmatrix} \tag{2}$$

The inverse kinematic of CDPR is like as.

$$|l_i|^2 = |a_i|^2 + |r|^2 + |\mathbf{R}b_i|^2 - 2a_i\left(r + \mathbf{R}b_i\right) \tag{3}$$

Below equation shows the relationship between kinetics, statics and dynamics of CDPR.

$$\begin{bmatrix} u_1 & \cdots & u_m \\ b_i \times u_1 & \cdots & b_m \times u_m \end{bmatrix} \begin{bmatrix} \tau_1 \\ \vdots \\ \tau_m \end{bmatrix} + \begin{bmatrix} \mathbf{F}_p \\ \mathbf{M}_p \end{bmatrix} = 0 \tag{4}$$

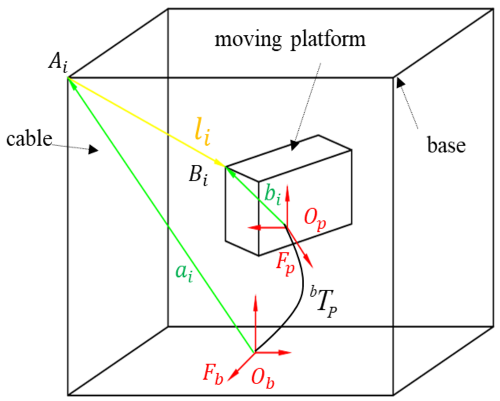

Figure 3. General kinematics of the cable robot (6 DOF; 8 cables)

Eq. (4) can be written as.

$$A\tau + \omega_p = 0 \tag{5}$$

Where: τ is cable tension vector (m x1); A is Jacobian matrix of CDPRs (n x m); $_p$ is vector of the external force acting on the center of gravity of the moving platform (n x 1).

Wrench closure workspaces (WCW) are a collection of flexible moving platform positions where the cables can come into positive tension contact with external wrenches. In other words, WCW is a collection of poses that a mobile platform can perform; this means that for any wrench f in WCW, there is a cable tension vector τ > 0 such that A + f = 0. We must calculate the combined force of tension for each MB posture using formula (10). Inversed matrix A, which may be obtained by inverting the matrix, balances the external forces[2].

$$\tau = A^{-1}\omega_p \tag{6}$$

III. Modeling the Friction between the Pulleys and the Bearings

Whenever pulleys or cables are designed, it is important to define the friction forces contacting surface between them. To determine the tension T_j, which is necessary to pull the belt counterclockwise. Euler-Eytelwein equation with kinetic friction between the surface of pulley and cable , wrapping angle a_i in of the i^{th} pulley, $_p$ is the friction coefficient. The schematic of a pulley system is shown in Fig. 4.

$$T_j = T_{j-1} e^{\mu_p \alpha} \tag{7}$$

The string's elasticity and gravity are ignored. In the case of force equilibrium, a force Fr is acting to guide the pulley with velocity v in the same direction as T_j, as defined by below equation.

$$T_j = T_{j-1} + \operatorname{sgn}(v) F_{R,j} \tag{8}$$

T_j, T_{j-1} the tension before and after the pulley. The pulley's friction force is determined by Coulomb coefficient of friction and viscous friction parameter F_{pv}.

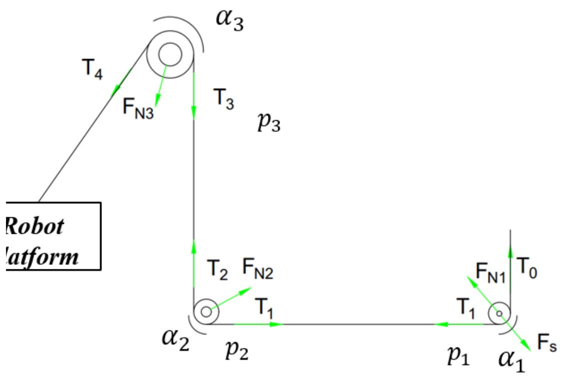

Figure 4. The guide of three pulleys for a cable

$$F_{Rj} = \mu_i F_{N,j} + F_{pv}|v| \tag{9}$$

Where: $F_{N,j}$ is the normal force to pulley j[th].

It is possible to determine the normal force from both the first and second tensions applied to the pulley by the cosine law. The Coulomb friction in the static model can be described as follows.

$$F_{N,j} = \sqrt{T_{j-1}^2 - 2T_{j-1}T_j \cos\propto_j + T_j^2} \tag{10}$$

$$F_{Rj} = \mu_j F_{N,j} \tag{11}$$

For greater precision, both Coulomb and viscous friction should be considered. The viscous impact is too minimal because our CDPR system operates at a speed of less than 10 m/s. As a result, viscous friction is omitted in this analysis. We can also regulate the pose by taking use of the Coulomb friction term's simplicity.

$$F_{Rj} = \left[\mu_j \cdot \sqrt{n_j^2 - 2n_j \cos(\alpha_j) + 1}\right] T_j = \lambda_j T_j \tag{12}$$

$$\sum_{j=1}^{3} F_{Rj} = \sum_{j=1}^{3} \prod_{k=1}^{3-j} n_k \left[\mu_j \cdot \sqrt{n_3^2 - 2n_{3+1-j}\cos(\alpha_j) + 1}\right] T_1 \tag{13}$$

Coulomb friction, on the other hand, has limitations in that it ignores pre-sliding dynamics at low velocities. Dahl friction can be used to model the pre-sliding dynamics; these dynamics are nonlinear when the velocity is close to zero. The Dahl friction first-order non-linear ordinary differential equation is presented. The Dahl friction model can be expressed in the following way [13]

$$\frac{dF_{d,j}(T_j)}{dx} = \sigma\left[1 - \frac{F_{d,j}(T_j)}{F_{Rj}}\operatorname{sgn}(v)\right]^{\beta} \tag{14}$$

$$F_{d,j}(T_j) = F_{Rj}\left(1 - e^{-\frac{\sigma|x|}{F_{Rj}}}\right)\operatorname{sgn}(v) \tag{15}$$

By simplifying the model with an exponential function α = 1, F_{Rj} is the maximum value of the friction force. The problem with the linear Dahl model is that the exponential function is related to position and represents the zero slope across the graph. $F_{d,j}$ is the Dahl friction of j[th] pulley, represents the slope of the friction with respect to position at the zero accrossing, that determine the pre-sliding range, x is the relative displacement between the cable and the pulley, and   define the pre-sliding shape and takes the value   = 1.[14,26] in most cases. Decoupling tension and friction factors can be utilized to generate a value for the tension that includes Dahl friction because Dahl friction is a function of Coulomb friction. Two of these factors are the loss factor and the friction coefficient. As a consequence, by incorporating equation, equation (5) for kinematics and dynamics may be enlarged. The Dahl model is part of a modified version of the kinematics equation, which is written as:

$$T+\sum_{j=1}^{3}\left[1-e^{\frac{-\sigma|x|}{\lambda_j T}}\right]\lambda_j \operatorname{sgn}(v)T=[A]^{+}\omega_p \tag{16}$$

$$\left[1+\sum_{j=1}^{3}\left(1-e^{\frac{-\sigma|x|}{\lambda_j T}}\right)\lambda_j \operatorname{sgn}(v)\right]T_{8\times1} \tag{17}$$

$$=[A]^{+}\omega_p+\left(I_{8\times8}-[A]^{+}[A]\right)h_v \tag{18}$$

$$S=\sum_{1}^{8}\left[T_{avg}-T\right]^{2}(0<T<1000N) \tag{19}$$

The elastic modulus is affected by the cable stiffness. A higher modulus of elasticity leads the gravitational sagging of the cable. As a result, we employ the Dahl model to describe its attributes and the friction compensation model to describe the pulleys. The model is configured to estimate friction, and the model's output is fed into the control system to adjust for it.

IV. Analysis of Tension with Dahl Friction in Cable

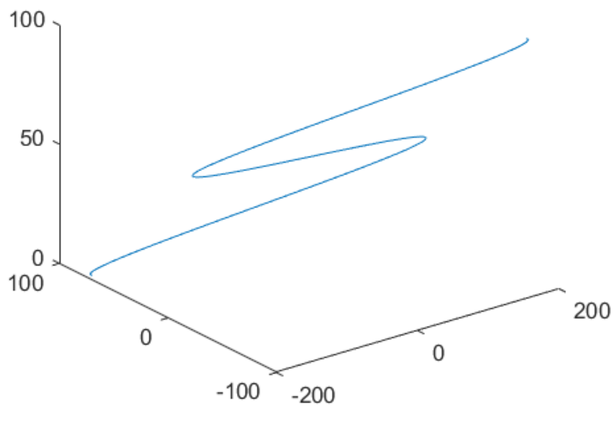

Figure 5. Parabolic trajectory of moving platform.

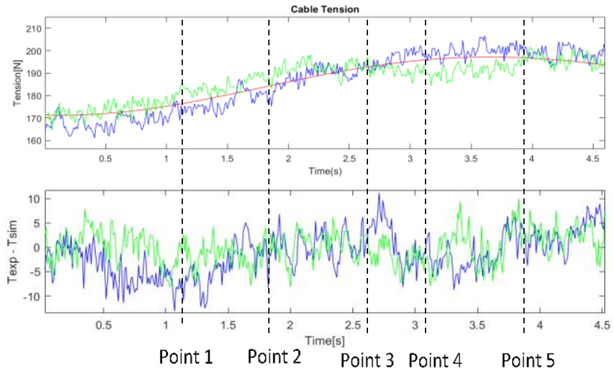

Figure 6. Pre-programmed motion with tension profile and error (velocity = 0.04 m/s).

CDPR is used in the 3D concrete construction process to create buildings by extruding layers of material. The robot is experimented moving along the trajectory shown in Fig. 5. The cable robot is programmed to print the trajectory illustrated in Fig.6 in this experiment. The tension algorithm calculates tonnage changes during printing to the best of its ability. The system is programmed to follow the desired path with two layers: printing velocity is 0.04 m/s, and extruder speed (Se) is 0.1 kg/s. The end cable tension is measured by the force sensor, which is placed near the winch. The simulation results are compared with those measured at the force sensor when the terminal effect is preprogrammed to evaluate the coulomb and dahl friction model in equation (15),(13). Table 2 summarizes the friction parameters used in the simulation. [9]Details on the selection of parameters have been studied previously [7][8]is the most influential parameter on the front slip range, which indicates the dynamic friction characteristics. Due to the fact that is different, dynamic friction has an effect on cable tension. Dahl friction stabilizes more quickly as increases as a result of the smaller pre-slip range. In this study's experimental technique, we chose a value of 500 when modifying[13]. Trajectory of experiment is performed by Eq. (20).

$$\begin{cases} x=200.\sin(5-u) \\ y=15.(15-u) \\ z=10.u \end{cases} \tag{20}$$

In Fig. 7, the total errors over the computed range of motion, as well as the mean and standard deviation of all coulomb and Dahl errors, are 10.58±3.37 N and 7.26±1.56 N. Furthermore, from (points 1 to 5) there is a clear transition in the Coulomb force. This selection's Dahl friction model is close to the experimental results. The coulomb friction is discontinuous and close to zero at the transition area. Dahl friction, on the other hand, remains in the transition range since it can simulate pre-slip at 0.04 m/s.

The standard deviation has decreased by 47%. In other words, when working at 0.04m/s, the Dahl model is more accurate. With that said, the most important aspect to consider is pre-slip if the system requires accuracy in position or motion transitions. As a result, string tension should be approximated using Dahl friction for high precision control.The robot was controlled using Tia Portal on a Windows PC with a 1 ms cycle time. Ethernel is the fieldbus protocol. Each cable has a stainless cable force sensor with a measuring range of 500N for force measurement. The force sensor's analog output signal is digitized in A/D converters and transferred to the control system through the field bus. Fig. 8 provides an overview of the PLC friction model experiment. The signal from the 8 force sensors F_s, the set point of the cable length and the winch speed l_{set}, v_{set}, and the shape based on the winding angle of the end pulley in the reverse kinematics module are all inputs to the parameter. Because set point velocities are utilized, the model is constantly ahead of the real friction. Because the output of the Dahl model is time-varying and compatible with the real-world friction model. Cable force measurement, in addition to cable force control, may be utilized to figure out what forces are at work on the platform (6). On the platform, the load was calculated and cable elongation was taken into consideration.

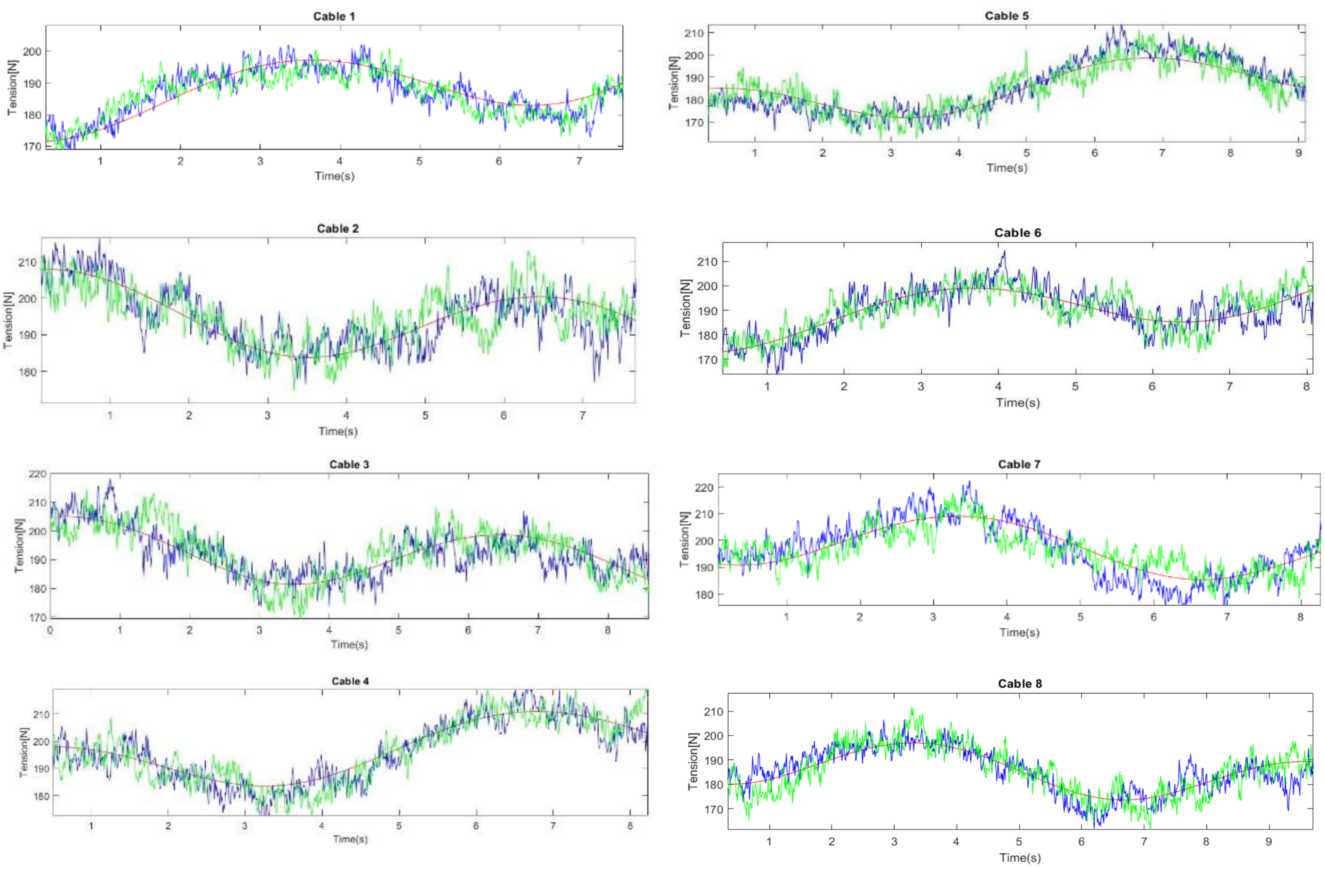

Figure 7. Tension profile for each cable

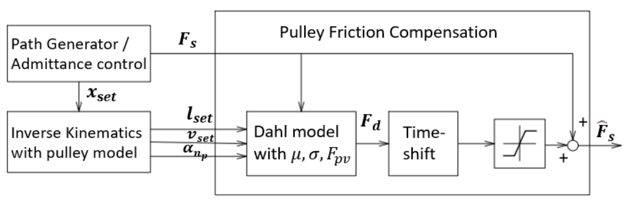

Figure 8. Experiment with the PLC friction model

Using the Dahl model, we were able to improve relative accuracy by almost 40% under changing loads. may be utilized to figure out what forces are at work on the platform (6). On the platform, the load was calculated and cable elongation was taken into consideration. Using the Dahl model, we were able to improve relative accuracy by almost 40% under changing loads. Hysteresis should be kept to a minimum, and the torque recorded will be influenced by the direction from which the posture is taken. To investigate the effect of pulley friction on wrench measurement, we designed the robot to cross a point cyclically in all six degrees of freedom. To survey the effect of pulley friction on wrench measurement, we designed the robot to cross a point cyclically in all six degrees of freedom.

The measurement data is summarized in Fig.9, which also illustrates the effect of pulley friction on the wrench's measured item. To do this, the real wrench is calculated and linked to the time-shifted ordered acceleration and gravity. Oscillations in the end-effector affect the resulting signal.With a weight of 500 N, the hysteresis oscillates in the same direction as gravity. Compensating friction can compensate for significant hysteresis in reciprocating motion. The robot's z-axis research hysteresis curve is relatively limited, thus friction compensation is employed based on the direction of the wrench change. The hysteresis can be almost adjusted via friction compensation to a width of only 5N.

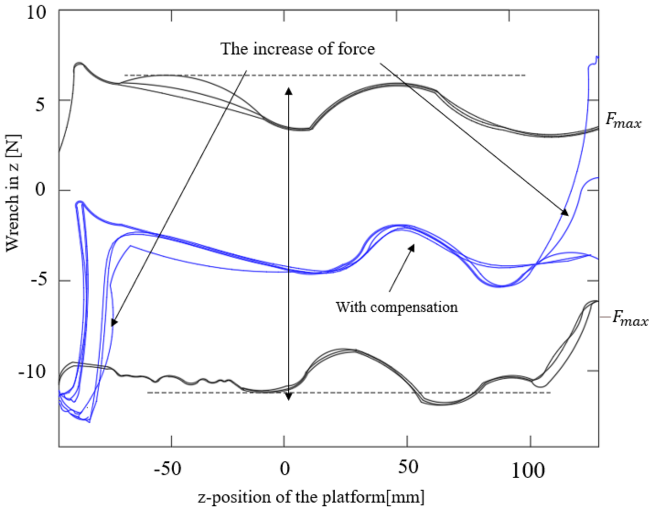

Figure 9. Improvement of the wrench hysteresis

V. Conclusion

In this paper , friction forces affected on the control of a drive robot with parallel cables was verified. The string tension was estimated for an 8-string robot with six degrees of freedom. To compensate for the force sensor's inaccuracy, use the appropriate friction model . In force measurements, experimental tests of a parallel robot program in building enhanced cable accuracy by 65 %. The proposed ANN which is based on location and velocity measurements, can properly predict the force distribution of the end effect device. This new technology could be used in CDPR systems designed to manage enormous loads in the future. To improve the application of CDPR in industry, an advanced control algorithm for a hybrid force and position controller will be created.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

T.T.P.T. performed the document preparation, data collection; T.T.P.T. analyzed the results and wrote the first draft of the manuscript; the manuscript was revised by N.T.T. N.T.T. is a corresponding author. All authors contributed to conceptualization and design of the study structure and content; all authors had approve d the final version.

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