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RESEARCH, ANALYZE AND EVALUATE THE INFLUENCE OF CABLE SAGGING ON THE POSITIONING ACCURACY OF CDPR

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SUMMARY OF PH.D. DISSERTATION

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CONTRIBUTIONS OF THE DISSERTATION

The issue of research, design, calculation, and control of Cable Driven Parallel Robots (CDPR) has been promoted in recent years. Through the analysis results of domestic and foreign research projects related to the research direction of the thesis, the PhD student realizes the goal of the project which is to research, analyze, and evaluate the impact of cable sagging on the position accuracy of CDPR. The research results and scientific contributions are summarized as follows:

- Identification of remaining issues, and research directions of the topic;
- Designing cable tension calculation algorithms DSA, QPA.
- Designing new cable sagging calculation algorithms TRDA based on trusted region algorithm and CSPA-ICSPA based on ANFIS. The algorithms are calculated, simulated, and give appropriate results, from this, an algorithm is designed to calculate the inverse kinematics problem for over-constrained CDPR taking into account the sagging of cables;
- Experimenting with the calculation results on CDPR, collecting and evaluating the results.

The analysis results show that cable sagging has a clear effect on the position accuracy of CDPR, the calculation model is built based on analysis and determination of components affecting cable sagging such as CDPR configuration, cable material, load, and especially cable tension distribution algorithms. Experimental results show that the cable sagging and cable tension calculation model has improved the position accuracy of CDPR, minimized calculation time, and simplified the calculation model. The model has also been used to design trajectories for real-time control applications, experimental results show that the system response is suitable for applications requiring high speed and load in large workspaces. From the results of this research, new research directions can be expanded such as developing new models to optimize workspace, determining cable tension distribution for over-constrained CDPRs, calculating sagging of cable, and vibration analysis, thereby simplifying the mathematical model and shortening calculation time, easily deploying complex CDPR configurations at low cost.

CHAPTER 1: INTRODUCTION

1.1 Rationale of the research

In the process of researching and applying CDPR, especially for large CDPRs, minimizing position errors plays an important role in controlling and operating CDPR. Sources affecting the position error of CDPR are presented in Figure 1.1: The first parameter is mechanical machining and assembly error including fixed frame structure, moving platform, and cable configuration that directly affects position error; The second parameter is the controller's error, including basic parameters of the actuator such as position accuracy, velocity, resolution, feedback signal measurement device; The third parameter is interference due to external forces, the distinctive feature of CDPR is that the cable must always be in a state of tension - positive tension - and ensure the system's equilibrium constraint conditions, thus external forces can distort the input constraint conditions for the cable tension distribution problem; The fourth parameter is the influence of friction of transmission components such as cables, pulleys, and winches; Finally, there is the influence of cable sagging, this parameter only found in cable transmission mechanisms. For non-elastic cables, the larger the size, the greater the cable sagging; For elastic cables, the greater the tension, the greater the cable elongation. The model for determining cable sagging is a system of nonlinear equations with input parameters being cable tension, CDPR kinematics, cable mass, external forces, and elasticity of the cable. Through surveys, it has been shown that the issue of research on the effects of design parameters of CDPRs is very important, especially for large CDPRs, because the cable tension, mass, elasticity, and length of the cable will cause cable sagging, distorting the results of the control trajectory position problem as well as the stiffness of the MP. Therefore, the project "Research, analyze and evaluate the influence of cable sagging on the position accuracy of CDPR" was carried out to study the effects of cable tension and cable sagging on the CDPRs, serve as a foundation for research into implementing large space CDPRs into practice, improving the accuracy and flexibility of different CDPR configurations. In particular, synthesizing the relationship between tension distribution and sagging of the cable has a great impact on position accuracy when controlling CDPRs, simplifying the calculation process and applying common control algorithms will reduce research time and manufacturing costs when applying CDPR in practice.

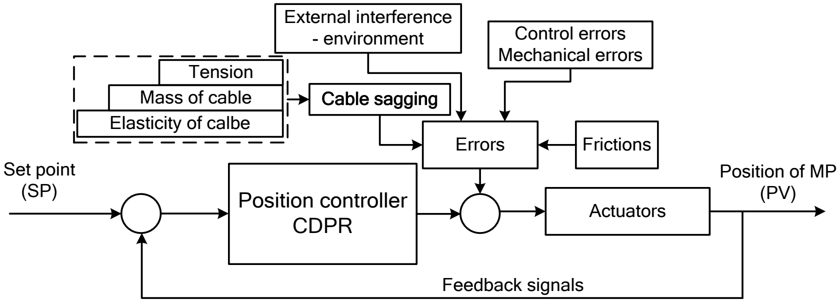

Figure 1.1: Parameters affecting CDPR position error

1.2 Research subjects

The research object of the thesis is a parallel robot configuration driven by cables. In particular, the research content focuses on the inverse kinematics problem with constraints on cable tension distribution, cable sagging, and boundary conditions of over-constrained CDPR.

1.3 Research objectives

The overall goal of the thesis is to research and develop the inverse kinematics problem of CDPR with algorithms to determine cable tension, and cable sagging and evaluate the impact of cable sagging on the position accuracy of the CDPR.

The specific goal of the thesis is to design algorithms to calculate cable tension and cable sagging using soft computing techniques to shorten calculation time, and improve the accuracy of the cable sagging calculation algorithm, with a mean square error of sagging less than 0.5mm and the calculation time is reduced by less than 20% compared to the numerical method with the given boundary conditions. Integrate the problem of cable tension and cable sagging into the CDPR inverse kinematics problem, thereby analyzing and evaluating the effects of cable tension and cable sagging on the position accuracy of the CDPRs with the following conditions: external force, load, CDRP configuration, and equilibrium conditions. The research results are experimented on CDPR to evaluate the effectiveness of the calculation models.

1.6 Scientific contributions

Scientific contributions of the thesis: Designing algorithms to determine cable tension distribution with flexible optimization criteria to be able to choose optimal conditions corresponding to a specific CDPR structure and boundary conditions of impact force, based on these results, analyze the impact of cable tension on the workspace of CDPR; Design 3 algorithms to determine cable sag based on the Trust region algorithm and ANFIS according to the conditions of cable tension, cable characteristics, and specific CDPR configuration. Integrate the problem of cable tension and cable sagging into the inverse kinematics calculation algorithm of CDPR, and simulate, collect, and evaluate results when applying the algorithm to determine cable sagging compared to other methods for over-constrained CDPR. Analyze the impact of cable tension distribution and cable sagging on the position accuracy of CDPR, evaluate the relationship between cable tension, CDRP structure, cable sagging, and elasticity of the cable winches; Experiment and evaluate results on a large CDPR with 6 degrees of freedom driven by 8 cables for complex tasks such as moving heavy objects, path interpolation, and virtual reality motion simulation.

CHAPTER 2: OVERVIEW OF CDPR

2.1 Basic structure of CDPR

CDPRs with moving platforms are controlled by adjusting the length and tension of the driven cables instead of directly affecting the rigid elements of the system with rotary or reciprocating motors. Compared to the robots with rigid links, using cables to drive robots allows motors and gearboxes of large size and mass to move from the moving platform to the base frame of CDPR, leading to a reduction in the mass and inertia of the moving platform. This change helps the robot accelerate faster and can be designed with smaller, cheaper motors and less material.

2.2 Overview of CDPR

CDPR has a complex structure and constraints because of the unidirectional nature of the driven cable, therefore, designing, calculating, and implementing CDPR applications is a big challenge. In particular, the CDPR kinematics[25][26] and dynamics[27][28] problems must deal with components that affect accuracy caused by design and calculation issues such as cable tension, external force, or the influence of pulley size, especially cable sagging for large CDPRs or CDPRs driven by elastic cables. In particular, external force, robot structure, workspace, and cable tension distribution have a direct impact on the sagging of the driven cable, so the survey of research references related to the research direction focuses on 3 main issues: calculating workspace, distributing cable tension and calculating sagging of driven cables.

The workspace of CDPRs has many forms depending on the input conditions, often related to the design structure, external forces, cable tension distribution, cable tension limits, feasibility conditions to control, and types of disturbances due to working conditions [29-59]. Calculating cable tension distribution is one of the important issues in researching and implementing CDPRs, especially FC-CDPRs, and OC-CDPRs, because there are many cable tension solutions corresponding to a pose of moving platform (end effector), mathematical models to solve this problem focus on finding solutions that satisfy specific optimal conditions, shortening calculation time for real-time applications, calculate solutions for applications with variable loads or other disturbances such as wind when working outdoors[60-90]. Calculating the sagging of transmission cables is an issue of great research interest because cable sagging greatly affects position accuracy in the design and calculation of large CDPRs or elastic cables. The cable sagging model is highly nonlinear and is especially directly related to the cable tension and applied external forces, as well as the configuration of the CDPRs. Research on calculating cable sagging is often based on Irvine's Catenary equation model, however, this model is highly nonlinear and can only be calculated using an iterative method. Computation time is a problem that needs to be solved for real-time control applications. Some research calculates cable sagging by linearizing some relationships of elements in the mathematical model, this can reduce calculation time but will limit the application object because of constraints on the configuration and operating conditions of CDPRs [91-120].

2.6 Remaining problems

Research on the impact of sagging on the workspace and cable characteristics shows that the workspace and cable tension distribution for straight and sagging cable models are different, the tension of sagging cable is not the same as the tension for the straight line model and is not constant across the entire cable. Most models for calculating cable sagging are based on Irvine's cable catenary equation model, due to high nonlinearity, solving the problem of finding cable sagging to compensate for the inverse kinematics is time-consuming, making it difficult to design real-time control applications, offline computing experiments use optimization algorithms that solve CDPR inverse kinematic in 0.4 seconds [93]. Some studies have also been conducted to simplify the calculation model by linearizing the relationship between cable tension components, but the results are limited in certain conditions and have not been verified experimentally [97-98]. Soft computing techniques are also being tested and have shown potential results [121-123], however, the results have not been analyzed in detail nor applied to different CDPR configurations. Applications that require high position accuracy such as trajectory control and pick-and-place position control need an accurate but not too complicated mathematical model to simplify the design, calculation, and implementation of the controller. The remaining problems in cable sagging calculation studies will be focused on in the following section: Modeling basic problems of CDPR; Determining and designing an algorithm to calculate parameters that affect position accuracy due to cable tension, cable sagging, and elasticity of actuators, shortening the time to calculate tension distribution according to given constraints; Build a cable sagging calculation model for specific CDPR configurations, improving calculation time. Integrate calculation algorithms into the CDPR controller based on research results, experiment, and evaluate the results.

CHAPTER 2: THEORETICAL FOUNDATIONS

3.2 Kinematic problem of CDPR

Figure 3.2 shows the general kinematic diagram of CDPR, in particular, the main reference frame is denoted as the B, the frame representing the moving platform is the E. $\mathbf{x} = (\mathbf{r}, \mathbf{R}) \in \mathbb{R}^n$ is the vector representing the direction and position of E frame in B frame, where *n* is the number of degrees of freedom of CDPR. According to the vector diagram in **figure 3.2**, we can obtain the formula for calculating vector $\mathbf{l_i}$ $(i = 0 \ldots m)$ corresponding to the MP configuration:

$$\mathbf{l_i} = \mathbf{a_i} - \mathbf{r} - \mathbf{R}\mathbf{b_i} \tag{3.1}$$

The length of the cables can be obtained from equation (3.2).

$$|l_i| = \|\mathbf{l_i}\| = \sqrt{[\mathbf{a_i} - \mathbf{r} - \mathbf{R}\mathbf{b_i}][\mathbf{a_i} - \mathbf{r} - \mathbf{R}\mathbf{b_i}]^T} \tag{3.2}$$

where vector $\mathbf{a_i}$ is the coordinates of fixed cable points A_i in the B frame, vector $\mathbf{b_i}$ is the coordinates of moving cable points B_i in the E frame and the unit vector $\mathbf{u_i}$ represents the direction of the cable $\boldsymbol{l_i}$, $\mathbf{R}$ is the matrix representing the direction of the E frame in the B frame according to Euler rotation.

3.3 CDPR velocity

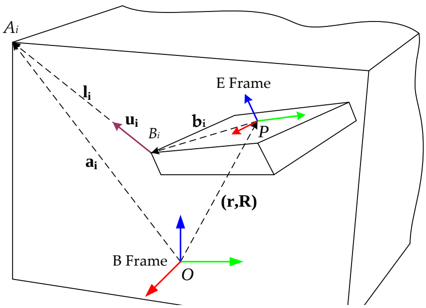

Figure 3.2: General kinematic model of CDPR

The velocity problem of CDPR represents the relationship between the velocity of the MP and the velocity of the driven cable or the velocity of the cable distribution motor. Let $\dot{\mathbf{r}} = [\dot{x}, \dot{y}, \dot{z}]^T \in R^3$ be the linear velocity of the center of the moving platform Op in the B frame, $\boldsymbol{\omega} = \begin{bmatrix} \dot{\theta}_x & \dot{\theta}_y & \dot{\theta}_z \end{bmatrix}^T \in R^3$ is the angular velocity of the MP around the three axes x, y, and z of the B frame, $\mathbf{v} = \begin{bmatrix} \dot{\mathbf{r}} & \boldsymbol{\omega} \end{bmatrix}^T \in R^6$ representing the MP's velocity vector including both the linear and the angular velocity. Let **J** ($n \times 6$) be the Jacobian matrix of CDPR, Differentiating equation (3.1) concerning time, we obtain the inverse velocity kinematic model as equation (3.8).

$$\dot{\mathbf{l}} = \mathbf{J}.\mathbf{v} \text{ where } \dot{\mathbf{l}} = \begin{bmatrix} \dot{l}_1 & \dot{l}_2 & \dots & \dot{l}_n \end{bmatrix} \quad (3.8)$$

3.4 Equilibrium equation

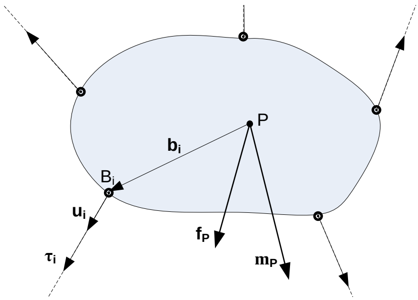

Figure 3.3: Diagram of forces acting on the moving platform

The equilibrium equations represent the relationship between the external force and the cable tension acting on the MP. To satisfy the equilibrium equation of CDPR or ensure the MP is in equilibrium, the sum of the applied force and the cable tension must satisfy the following equation.

$$\sum_{i=1}^{m} \boldsymbol{\tau}_{\mathbf{i}} + \mathbf{F}_p = 0 \quad (3.13)$$

$$\sum_{i=1}^{m} (\mathbf{b}_{\mathbf{i}} \times \boldsymbol{\tau}_{\mathbf{i}}) + \mathbf{M}_p = 0 \quad (3.14)$$

Where $\mathbf{f_p}$ and $\mathbf{m_p}$ are the vectors of force and moment, respectively, due to the external force acting on MP; $\boldsymbol{\tau}_\mathbf{i}$ is the cable tension vector that each cable exerts on the moving platform and vector $\mathbf{b_i}$ represents the position of the cable attacht point B_i on MP from Op in the E frame **(Figure 3.3).**

3.5 Dynamics of CDPR

In this section, the dynamic model is developed, taking into account different cable models and subsystems, from the results of **[121],** the dynamic equation of CDPR has the form:

$$\mathbf{I}\dot{\mathbf{v}} + \mathbf{C}\mathbf{v} + \mathbf{w}_p + \mathbf{w}_g = \mathbf{A}\boldsymbol{\tau} \tag{3.20}$$

Where **I** is the inertia matrix of the MP in the B frame, **C** is the matrix representing the centrifugal and Coriolis force components, $\mathbf{w_p}$ is the external force vector and $\mathbf{w_g}$ is the gravity vector. In the general case, the center of gravity G of the MP does not coincide with the origin of the frame E. Equation (3.20) shows the relationship between kinematics, statics, and dynamics of CDPR. In the following sections, the parameters identified in this section will be developed and analyzed to determine the design parameters of CDPR including workspace, tension distribution, sagging of cables, and integration into the controller.

3.6 Workspace of CDPR

For CDPR, cable tension greatly affects the defined workspace. Figure 3.3 shows that, to balance any combination of external forces and moments ($\mathbf{f_p}$, $\mathbf{m_p}$) acting on the moving platform, the cables must create appropriate tension. The forces and moments acting on CDPRs can be obtained from the following balance equations:

$$\mathbf{A}\boldsymbol{\tau} + \mathbf{w_p} = \mathbf{0} \tag{3.26}$$

where: $\boldsymbol{\tau}$: Cable tension vector (mx1); $\mathbf{A}^\mathbf{T}$: Jacobian matrix of CDPR (nxm); $\mathbf{w_p}$: vector of an external force acting on the center of mass of the MP (nx1).

From (3.26), CDPR's Wrench Closure Workspace (WCW) defines a set of poses of the moving platform in which the cables can balance any external force with positive tension. Or, WCW is the set of possible positions of the moving platform, which means that for any external force **f** in **[f]**, there exists a cable tension vector $\boldsymbol{\tau} > \mathbf{0}$ such that $\mathbf{A}\boldsymbol{\tau} + \mathbf{f} = \mathbf{0}$. In case CDPR has more cables than degrees of freedom, the **A** matrix will be rectangular (nxm) with n being the number of degrees of freedom and m being the number of driven cables. This leads to the existence of more than one tension distribution solution for a given position of the moving platform. Several methods for determining the existence of an inequality system with a solution have been used, such as pseudo-inverse matrices, linear optimization, interval analysis, etc.

CHAPTER 4: DESIGN OF ALGORITHM FOR INVERSE KINEMATIC WITH CABLE TENSION AND CABLE SAGGING

4.2 Tension distribution algorithm

Calculating cable tension distribution for CDPRs is a complex problem in the calculation and design process. Cable tension is related to important problems such as determining the workspace, calculating the stiffness of the mechanical system, determining the power of the motor, designing the controller, and calculating cable sagging. The problem to be solved is to find a solution for positive cable tension for MP positions that satisfies the following equilibrium equation:

$$\mathbf{A}\boldsymbol{\tau} = -\mathbf{w}_{\mathbf{p}} \text{ with } \mathbf{0} < \boldsymbol{\tau}_{\mathbf{min}} \leq \boldsymbol{\tau} \leq \boldsymbol{\tau}_{\mathbf{max}} \qquad (4.1)$$

Where **A** *(n×m)* is the structure matrix of CDPR; $\boldsymbol{\tau}$ *(m×1)* is the tension vector; $\mathbf{w}_{\mathbf{p}}$ *(n×1)* is the vector of external forces and moments acting on the center of mass of MP includes both inertial forces and gravity; $\boldsymbol{\tau}_{\min}$ is the lower limit of cable tension to ensure the cable is always in a tension state and $\boldsymbol{\tau}_{\mathbf{max}}$ is the upper limit of cable tension to ensure that the motor or cable is not overloaded. In this section, the cable tension distribution algorithm is designed for CDPRs with 1 DOR or more based on Linear programming and Quadratic programming. The results of this method are analyzed and evaluated for impact on related problems in subsequent research such as controller design and calculation of effects due to cable sagging.

4.3 The inverse kinematics with cable sagging based on the Catenary equation – Irvine

4.3.1 Catenary equation – Irvine [91]

The cable sagging model assumes that the cable is deflected only by its weight, ignoring the wind and uneven weight distribution. Consider a cable suspended between two points B and M, as shown in Figure 4.10, where B is the cable attach point on a fixed frame, M is the cable attach point on a moving platform, L_S (m) is the free length (Euclide norm) between B and M, L (m) is the (actual) cable length between B and M, g (m/s2) is the gravitational acceleration, (x_m, z_m) is the coordinates of cable at attach point on MP in the local frame, E (Pa) is the elastic modulus of cable and A (m2) is the cable cross-section. All coordinates are in the local frame attached to the vertical plane containing the cable. The term $\Delta L = L - L_s$ represents the deformation of the cable. When finding the cable length for a given position, consideration of the effect of cable sagging (i.e. mass of the cable) is necessary and cable tension is relevant in finding the cable length and cable sagging. Therefore, the kinematic and static problems (or quasi-static when ignoring the dynamic problem when controlling the moving platform at slow speeds) are coupled and must be solved simultaneously. The results of the kinematics and statics problems are the cable length and cable tension that are used as inputs to the cable sagging model, which is a nonlinear system and no analytical method can apply to solve it. Numerical methods can be used to find suitable solutions, the Trust-Region-Dogleg algorithm **[124]** is used to solve the equations representing cable sagging, this algorithm is defined as given a set of n nonlinear functions $F_i(x)$, where n is the number of elements in vector x, the goal of this algorithm is to find a vector x that makes all $F_i(x) = 0$. In this case, the sagging cable equations are rewritten as:

$$F_i = \begin{cases} \dfrac{|\tau_x|}{\rho_L g}\left[\sinh^{-1}\left(\dfrac{\tau_z}{\tau_x}\right) - \sinh^{-1}\left(\dfrac{\tau_z - \rho_L g L}{\tau_x}\right)\right] - x_m \\ \dfrac{1}{\rho_L g}\left[\sqrt{\tau_x^2 + \tau_z^2} - \sqrt{\tau_x^2 + (\tau_z - \rho_L g L)^2}\right] - z_m \\ \sqrt{\tau_x^2 + \tau_z^2} - \tau \end{cases} \tag{4.38}$$

where $n = 3, \qquad x = \begin{bmatrix} \tau_x & \tau_z & L \end{bmatrix}$

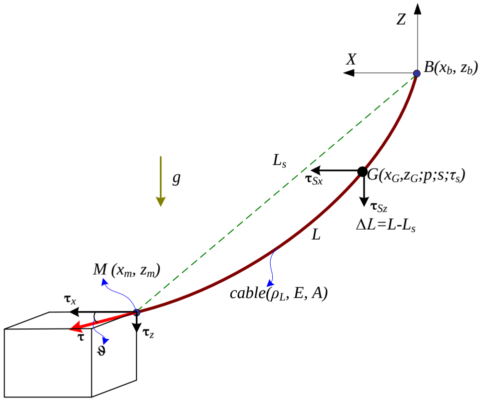

Figure 4.10: Catenary cable profile

This algorithm provides a set of solutions for each input condition (τ, X_m, Z_m), this data is the input of the algorithm used to find the cable tension distributions, with the hypothesis that the MP moves slowly. The Dual Simplex algorithm is used to find a set of tension force combinations such that the total objective function of the tension force is smallest, with the condition that the tensions must be within a given limit, the results of the kinematics problem and cable tension distribution are converted into the input of the cable tension distribution algorithm. In this section, the Trust-Region-Dogleg algorithm is used to calculate the cable length taking into account the cable sagging and the weight variation of the moving platform.

4.4.2 Cable sagging estimation algorithms based on ANFIS [124]

In this study, the ANFIS (Adaptive Neuro-Fuzzy Inference System) architecture is used to design two cable sagging estimation algorithms for large CDPRs: CSPA and ICSPA, the ANFIS model can be used to solve nonlinear functions, detect nonlinear elements directly in the control system, this feature can be consistent with the nonlinear model of the system of equations to calculate sagging according to the catenary equation. The trained data for the ANFIS models were obtained from the results of calculations using the Trust-Region-Dogleg (TRDA) algorithm [124] based on two cable tension calculation algorithms, Dual Simplex Algorithm (DSA) and Quadratic Programing (QPA). The cable sagging data obtained from ANFIS and the TRDA algorithm are compared and evaluated using the statistical tools of the evaluations, the results of these models are also applied to a CDPR with two degrees of redundancy. The CSPA developed for the inverse kinematics of CDPR considering the cable sagging is illustrated in **Figure 4.15**, the position vector of the MP (R^6) is used as input to the ANFIS models to calculate the cable sagging under kinematic and equilibrium constraints. Figure 4.21 shows the results of calculating the sagging of 8 cables when the robot moves along a 2m diameter circle with z = 1000mm. The simulated trajectory has a continuous shape which means all nodes lie within the WFW. Cable length varies from 3400mm to 5700mm with 126 nodes, the cable sagging is calculated using two methods: TRDA and CSPA based on the DSA algorithm to minimize the total tension of CDPR. TRDA produces a cable sagging curve with undulations, while the cable sagging curve predicted by CSPA is more continuous. The maximum error is 1.1111mm according to this trajectory, the largest errors tend to occur when the sagging changes suddenly in response to a sudden change in the corresponding tension, while the maximum RMSE is only 0.2521mm, which shows that the number of points has the large error is small, only occurring at points where the cable sag has a large change. In this trajectory, the cable compensation length ranges from 0mm to a maximum of 2mm, when the cable tension is greater than 300N, the sagging approaches zero (mm).

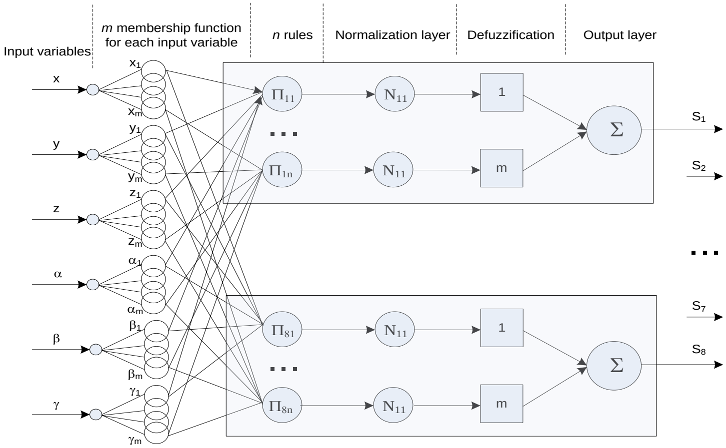

Figure 4.15: Proposed ANFIS architecture to predict cable sag

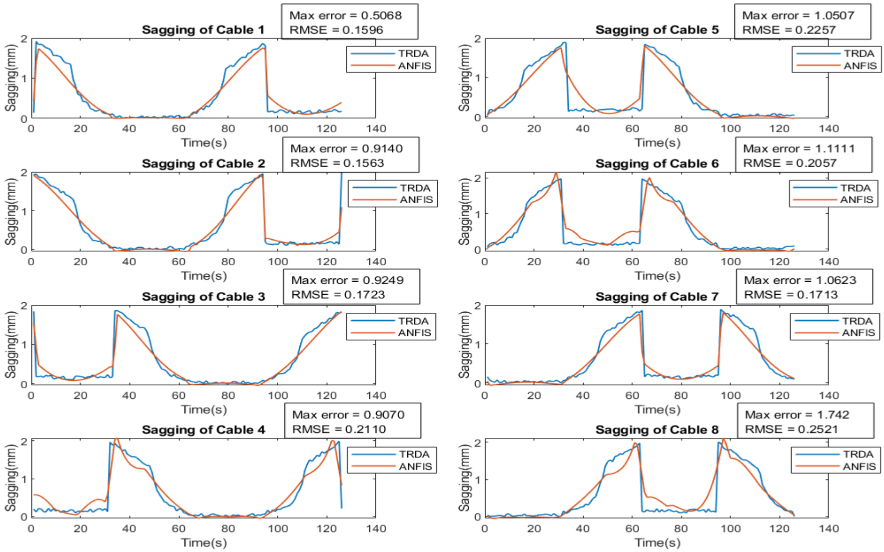

Figure 4.21: Sagging of 8 cables along a circular path of radius 1000mm-DSA

4.4.4 Improve Cable Sagging Prediction Algorithm based on ANFIS

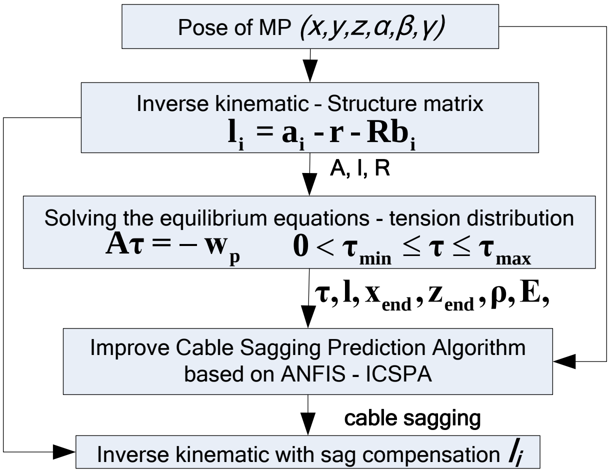

Figure 4.25 Inverse kinematic with ICSPA

A disadvantage of the CSPA algorithm is that it only applies to each specific tension distribution solution and CDPR configuration because the input is the position of the MP, this disadvantage limits the applicability of the CSPA algorithm. To solve this problem, an Improved Cable Sagging Prediction Algorithm based on ANFIS (ICSPA) - was built to overcome the disadvantages of CSPA, expanding its applicability to many different CDPR configurations, the ICSPA algorithm is also based on basic CDPR problems such as inverse kinematics, cable tension distribution, TRDA algorithm, and ANFIS model. The input data of ICSPA includes 4 variables: cable length l, z_{end} coordinates of the mobile cable attachment point, cable tension τ, and cable diameter d (**Figure 4.25**). These parameters are the results of inverse kinematics problems, tension distribution, and cable parameters without taking into account cable sagging. The model was built for a cable with a maximum length of 20m, and a maximum cable tension of 1000N, this is also the design parameter of the cable distribution winch for CDPR experiments in the following section.

Figure 4.27 shows the results of calculating cable sagging using the three methods TRDA, CSPA, and ICSPA in a circular path with a diameter of 1600mm on the same CDPR configuration with the QPA cable tension distribution algorithm. The results show that the cable sagging response according to ICSPA is more accurate than the CSPA method, approaching the values of the TRDA. In particular, ICSPA has a continuous form and is more similar to TRDA than CSPA, with cable sagging ranging from 0.0mm to 0.6mm, showing that the accuracy of the ICSPA method is significantly improved. To evaluate the calculation ability of the ICSPA algorithm with different CDPR configurations and tension distribution algorithms, ICSPA is used to calculate the cable sagging of the CDPR with a large size of 16×16×8m, with a mobile platform with a mass of 80kg and dimensions of 1x1x1m, the designed path is a circle with a diameter 5m at z = 2mm with an angle of inclination along the x-axis of 5 degrees. Calculation results show that the cable sagging value calculated by ICSPA closely follows the cable sagging value calculated by the TRDA, the calculated cable sagging value ranges from 1mm to 16mm, this also shows that the longer the cable, the greater the influence of cable length on cable sagging, specifically with a cable with a length of 15m and a cable tension of 140N, the cable sag is up to 15mm if the cable length is 10m and the cable tension is about 250N, the cable sagging is about 2mm. These show the nonlinearity of the cable sagging calculation model with Irvine's catenary cable equation according to cable tension, cable length, and cable position. Therefore, the ICSPA prediction method gives very good calculation results, suitable for application in predicting sagging of driven cables for large CDPRs.

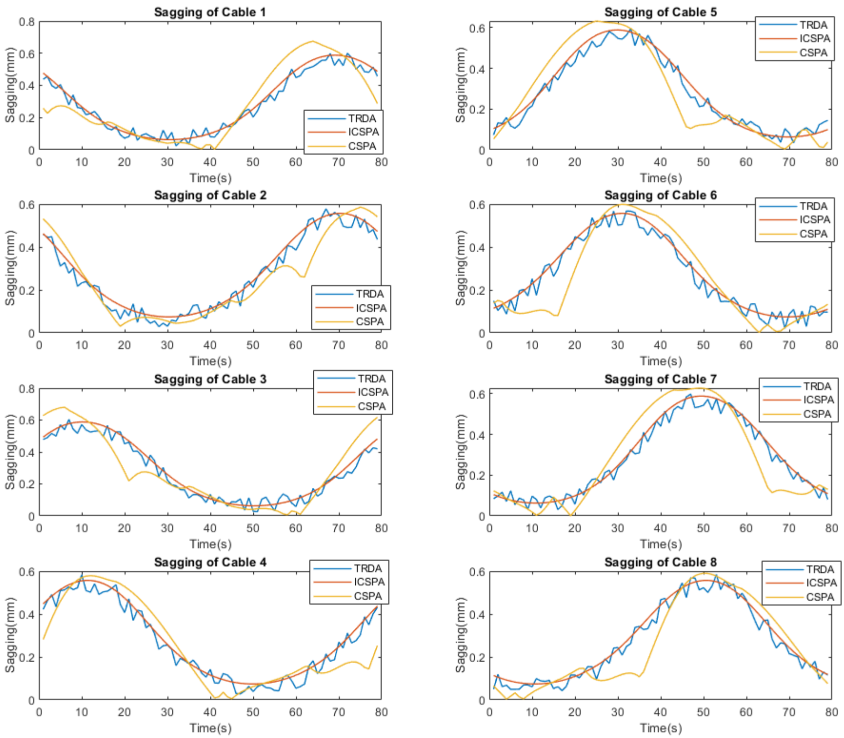

Figure 4.27: Sagging of 8 cables along a circular path

Table 4.8 provides a general comparison of design criteria such as calculation time, control trajectory continuity, response to cable tension distribution algorithms, and prediction accuracy with different CDPR configurations. The results show that the TRDA algorithm has an average calculation time, the calculated cable sagging has a continuous form according to the control trajectory, and this algorithm can accommodate all tension distribution solutions as well as any CDPR configuration, however slow computation times are an obstacle for applications that need a real-time response.

Table 4.8: Comparison of 3 cable sagging calculation algorithms

Evaluation criteria	TRDA	CSPA	ICSPA
Calculation time	average	good	good
Continuity along the control trajectory	good	good	Excellent
Calculation accuracy	good	average	good
Responds to cable tension distribution algorithms	all	According to each given algorithm	all
Applicability to various CDPR configurations	all	According to each given configuration	all

The CSPA algorithm has the fastest calculation time but depends on a specific tension distribution solution and a given CDPR configuration, which makes it difficult to change the CDPR configuration as well as the tension distribution method. The ICSPA algorithm has a larger calculation time than CSPA due to having to solve the problem of kinematics and cable tension distribution, but the calculation time is still reduced by more than 99% compared to TRDA and this algorithm can meet different CDPR configurations, and cable tension distribution algorithm with boundary conditions on CDPR size, cable tension limit and a given cable diameter. On the other hand, ICSPA gives accurate and continuous prediction values with a mean square error of less than 0.1mm, smaller than CSPA with a mean square error of less than 0.3mm under the same input calculation conditions. Thus, the simulation results show the suitability of the two models CSPA and ICSPA based on ANFIS built to calculate cable sagging for the inverse kinematics problem of CDPR. With the advantage of fast calculation time, these two models have potential applications for tasks that require high-speed control. Notably, ICSPA can be easily deployed for large CDPRs with a cable length of up to 20m for different control requirements. This result will be integrated into the controller and experimented on a large CDPR in Chapter 5.

CHAPTER 5: EXPERIMENT AND EVALUATION

5.4 Integrate the inverse kinematics with cable sagging into the controller

The transmission diagram of the cable distributors is shown in **Figure 5.1**. The structure of the control model of a cable distribution mechanism (considered as a joint) is depicted in **Figure 5.6**, this configuration is built on kinematic and dynamic problems including tension distribution solution and cable sagging calculation problem. The dynamic block is used to calculate the feedforward control signal for the controller due to the traction and friction forces acting on each motor shaft [134-135]. The system dynamics block is based on equation 3.20, in which the cable tension distribution τ_{ID} is obtained from the algorithm in Chapter 4, combined with the dynamic models 3.20 and 5.12.

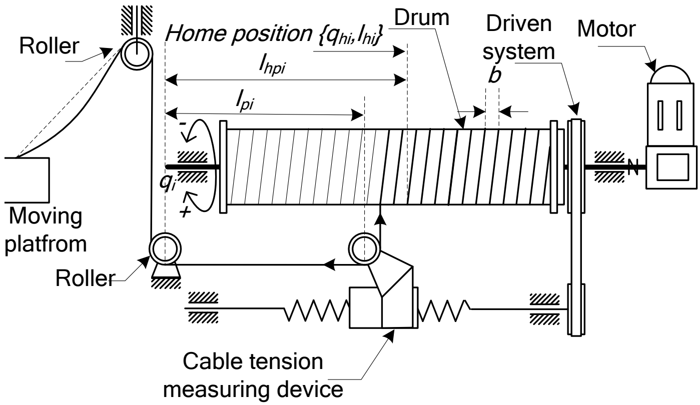

Figure 5.1: Transmission diagram of CDPR and cable distributor

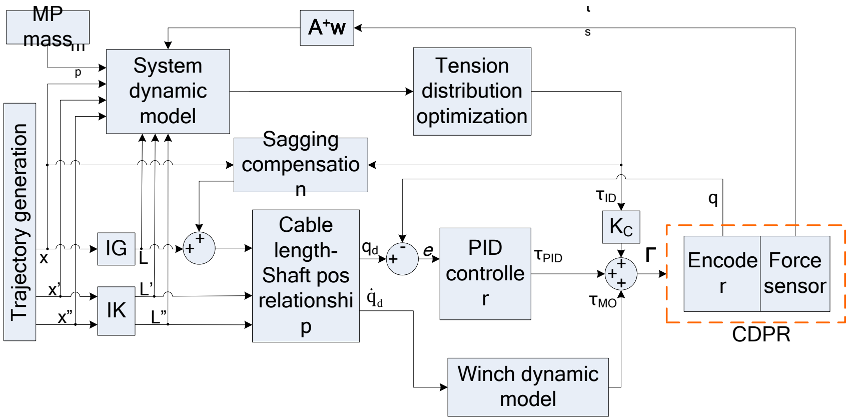

Figure 5.6: Structure of the cable distribution controller

Figure 5.7 is the structure of control model components established on Matlab Simulink, this model includes the blocks calculated in previous chapters. The 'Winch Dynamic' model block is established from equation 5.12 with friction components in the cable distribution winch. The PID controller block is a position controller with mathematical models 5.13 and 5.14. 'Trajectory - Dynamic - Tension Distribution – Sagging' block synthesizes the problems of trajectory planning, kinematics, velocity kinematics, dynamics, and cable sagging from input trajectory. The 'Kinematic-Velocity' block calculates kinematic problems, the output of this block is data used to calculate dynamic problems, cable tension distribution, and cable sagging. The Inertia Tensor block and the Symmetric Inertia Tensor matrix CDPR are components of the CDPR dynamic problem. The 'Dynamic Tension Distribution' block contains dynamic models and cable tension distribution algorithms, the output of this block is the tension of cables.

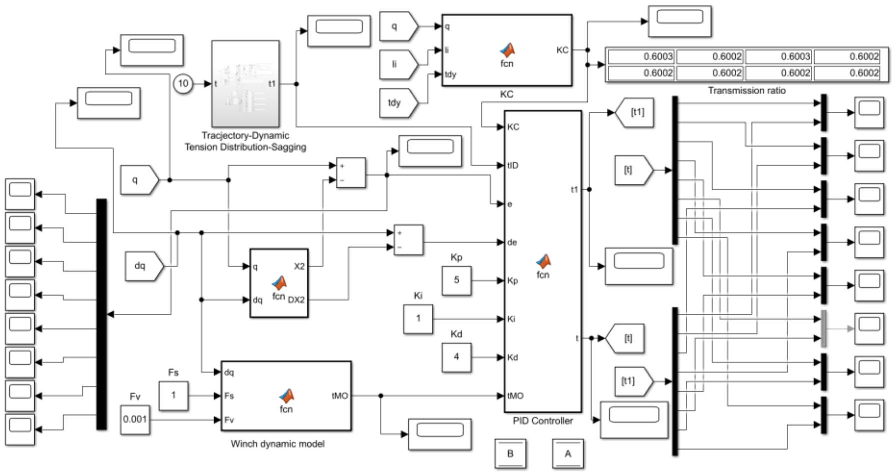

Figure 5.7: CDPR control model structure

5.5 Experiment and evaluation

Figure 5.10 is the CDPR used for the experiment. The section workspace and cable tension distribution demonstrated how to calculate the moving range based on the weight of the load, rotation angle, and MP position to ensure that the cable tension is always within a safe range. In practice, the cable tension values returned from the force sensors by visual inspection will return results that are within the estimated range and do not indicate overload even when the platform moves to points located at the constrained limit. Position accuracy is performed on 2 calculation models: without taking into account the influence of cable sagging and with a calibrator that compensates for cable sagging. The accuracy experiment is measured in three translation axes: X, Y, and Z, so the experimental process will let the CDPR draw basic paths such as straight lines or circles to measure accuracy along the X, and Y and move to locations in space to measure errors in the Z direction. The results are compared with the desired trajectory to measure the position accuracy in 2 cases, figure 5.14 is the experimental result of the position accuracy of CDPR. The CDPR draws two different colored paths overlapping each other, the red path is the trajectory without cable sagging compensation, blue path is the trajectory with cable sagging compensation, then measure the deviation between the two paths in the X and Y directions compared with the design trajectory to evaluate the position accuracy of the two cases. **Figure 5.15** is the joint trajectory corresponding to the circular trajectory obtained from the encoder of the servo motors, the shape of the continuous trajectory, responding according to the designed joint trajectory.

Figure 5.10: CDPR for experiment

The cable tension is measured along a circular trajectory from force sensors mounted on the cable distributors, the cable tensions vary between 50N and 300N, and the pattern of the cable tension is continuous according to the joint trajectory, this is consistent with the calculation results in previous chapters. Stable cable tension also shows the suitability of the designed control algorithm, this is an important result in CDPR control, controlling tension within given limits ensures rigidity and accuracy of the mechanism, thereby demonstrating the advantages of CDPR for requirements that require moving heavy loads with small actuators. In this experiment, the carrying load is 800N, while the cable tension ranges from 50N- 300N.

Figure 5.14: Measuring accuracy with circular trajectory

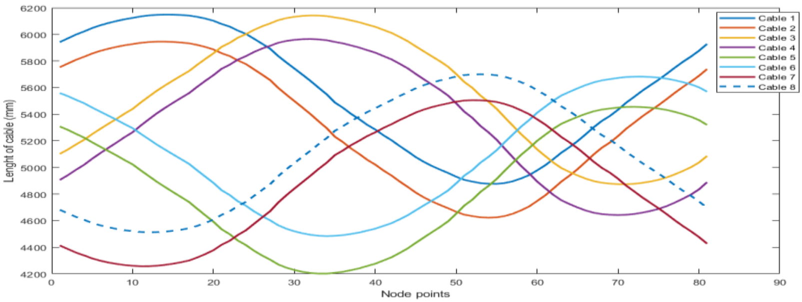

Figure 5.15: Length of the cable according to circular interpolation

Figure 5.18 shows the cable sagging compensation values in a circular path. This result is completely consistent with the simulated calculation model, in which the relationship between tension, length, and sagging of cables is guaranteed. Cable sagging varies from 0mm to 3mm according to the joint trajectory. **Figure 5.20** is the position error in the case of taking into account the cable sag, which fluctuates within ± 5mm compared to the case of not taking into account the cable sag, which is ± 8mm. The error in the z direction of both cases also shows similar results, this result shows that the position accuracy has improved significantly with the built cable sagging calculation model. Computational efficiency will increase as the robot size becomes larger because the effect of cable sagging is proportional to the workspace.

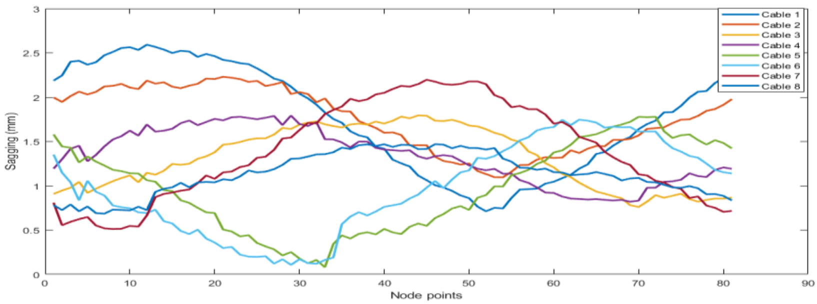

Figure 5.18: Cable sag value according to circular interpolation

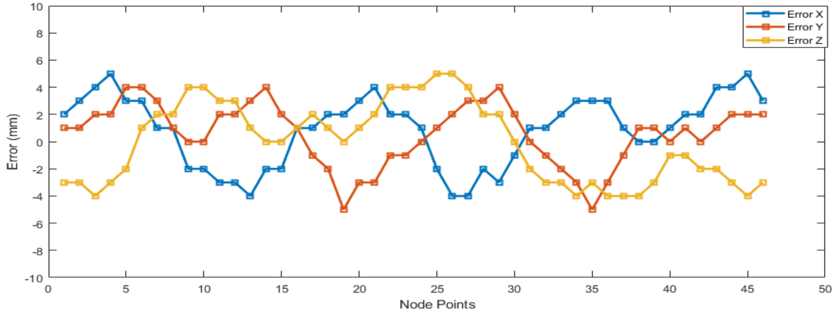

Figure 5.20: Position accuracy with cable sag compensation

Experimental results of spatial position accuracy and parallelism with cable sagging also show similar results, in which the response is very good with an error smaller than $\pm 0.8^0$ compared to the case without cable sagging compensation which is $\pm 2.2^0$. Experimental results of virtual reality motion simulation also show positive results, the position of the simulated cabin is controlled following the signal from the corresponding Game, and some cable tension values are smaller than the lower limit, but still greater than 0, ensuring positive tension during movement. This shows that tension distribution and cable sagging compensation are extremely important in the CDPR control process, especially for applications that need a real-time response, to ensure positive tension as well as direct control cable length compensation when tension changes suddenly outside preset limits.

CHAPTER 6: CONCLUSION

9.1 9.1 Research results of the thesis

Research and experimental results show that calculating the cable sagging is necessary to improve the position accuracy of CDPR, numerical methods and prediction methods were applied to calculate the inverse kinematics problem taking into account the cable sagging, thereby improving the computation time and accuracy of the inverse kinematics problem. Two algorithms to determine cable tension distribution have been built and tested, DSA with the optimal goal of minimizing total cable tension and QPA to continuously distribute tension and select the trend of tension distribution, with kinematic constraints and cable tension limits. The ANFIS model was used to build two cable sagging prediction algorithms: CSPA based on the kinematic structure of 6 DOFs – 8 cables over-constrained CDPR and ICSPA for different CDPR configurations. Parameters affecting cable sagging such as kinematic structure, cable tension, and cable tension distribution method (DSA, QPA, and FCDF) are also taken into account when creating input data for building the CSPA - ANFIS model. Meanwhile, ICSPA uses as inputs the cable coordinates converted from the MP position, cable tension, and cable parameters for a more general and accurate solution, while still ensuring calculation time. The ANFIS model can be used to determine sagging for CDPRs with fast calculation time and high accuracy. The calculation results show that the calculation time of the CSPA algorithm is 0.08% (99.92% reduction), and the calculation time of the ICSPA algorithm is 0.6% (reduced by 99.4%) compared to the TRDA method. Regarding calculation accuracy compared to numerical methods, ICSPA gives accurate and continuous prediction values with a mean square error of less than 0.1mm and is smaller than CSPA with a mean square error of less than 0.3mm under the same input conditions. Experimental results on CDPR with the inverse kinematics problem taking into account cable sagging show that the position accuracy has improved by more than 50% at ±4mm. The accuracy of direction or parallelism has an error of less than 1^0, which shows that the cable sagging calculation model gives results consistent with the simulation results. Based on the results of research and experiments on inverse kinematics problems that take into account cable sagging with the parameters that affect the determination of cable sagging, it is possible to conclude that: First, the calculation model is suitable for large-sized CDPR applications; Second, cable sagging directly affects the position accuracy of CDPR; Third, cable sagging and cable tension have a close relationship, the accuracy of the CSPA model depends on the cable tension distribution method and CDPR configuration, while ICSPA does not depend on the configuration and cable tension calculation method; Fourth, the calculation results are integrated into a controller with cable sagging compensation for 6 DOFs – 8 cables over-constrained CDPR. The results were tested on a CDPR with kinematics, dynamics, tension distribution, and cable sagging problems. Evaluation of experimental results and analysis of the influence of cable sagging on the position accuracy of CDPR shows that position accuracy has been improved when applying the algorithm to calculate the inverse kinematics problem with the cable sagging compensator. This result introduces a new research direction to simplify the calculation process, shorten calculation time, and improve the ability to deploy large CDPRs with complex configurations for applications requiring speed, large load, and high precision. Three algorithms for calculating cable sagging based on the Irvine equation are TRDA, CSPA, and ICSPA, showing a new research direction, that is to use soft computing techniques to develop algorithms to calculate inverse kinematic problems that take into account cable sagging with high accuracy and continuity for CDPRs with larger sizes and loads.

9.2 Outstanding issues

The CSPA algorithm predicts the cable sagging based on the coordinates of the MP and the cable tension, so the calculation model depends on the structure of the specific CDPRs and cable tension distribution method. The ICSPA has resolved the limitations of CSPA by generalizing the inputs according to the catenary cable model in Chapter 4. This method has the advantage of applying to any CDPR, however, the calculation time increases due to having to solve the problems of CDPR kinematics and cable tension distribution. In the next studies, the cable sagging calculation algorithm based on the ANFIS model or other soft computing models will be adjusted and applied to calculate the sagging of the cable and experimented with CDPR configurations with larger sizes and payloads.

LIST OF PUBLICATIONS

[1] Tuong Phuoc Tho, Nguyen Truong Thinh, "Analysis and Evaluation of CDPR Cable Sagging Based on ANFIS", Mathematical Problems in Engineering, vol. 2021, Article ID 4776317, 20 pages, 2021. https://doi.org/10.1155/2021/4776317 **(SCIE - Q3, IF 1.576)**

[2] Tuong Phuoc Tho, Nguyen Truong Thinh, "An Overview of Cable-Driven Parallel Robots: Workspace, Tension Distribution, and Cable Sagging", Mathematical Problems in Engineering, vol. 2022, Article ID 2199748, 15 pages, 2022. https://doi.org/10.1155/2022/2199748 **(SCIE - Q2, IF 1.576)**

[3] Tuong Phuoc Tho & Nguyen Truong Thinh (2023) Evaluating cable tension distributions of CDPR for virtual reality motion simulator, Mechanics Based Design of Structures and Machines, DOI: 10.1080/15397734.2023.2265452, Volume 0, page 1-19. **(SCIE – Q1, IF 3.9)**

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[5] Tho, Tuong Phuoc, and Nguyen Truong Thinh. "A Study of Tension Distribution for Control of Planar Cable Driven Parallel Robot Using Quadratic Programming Algorithm" IJMERR 2022 Vol.11(7): 479-485 **(SCOPUS - Q3, IF 1.012)**

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[9] Tuong, Phuoc Tho, and Nguyen Luan Vu Truong. "Thiết Kế và Tính Toán Hệ Thống Phân Phối Cáp cho CDPR." Journal of Technical Education Science 19, no. SI01 (2024): 64-71.