Sagging Cable Analysis and Evaluation of 4-degree-of- freedom Cable Robot Using Adaptive Neural Fuzzy Algorithm

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***Abstract*—One of the most important problems in robot modeling and control of cable robots is the problem of inverse kinematics, that is, using the coordinate data of the end effector to calculate the corresponding joint variables. Especially with regard to the kinematics of the cable robot, the sagging of the driven cable can have a significant effect on the calculation of the cable length, and this is more evident when the cable length is large, for example in construction or agriculture applications, where needs a large workspace. The determination of cable deflection considers modeling the cable as a chain model rather than calculating the cable length as a straight-line model. Furthermore, due to the structure and constraints of cable robots or Cable Driven Parallel robots (CDPRs), the system modeling and simulation becomes complicated, thereby increasing the computation time. In this paper, we propose an algorithm of Adaptive Neural Fuzzy Inference System (ANFIS) that is used to solve the cable sag problem for the 4-cable robots. This model was applied to estimate the cable sag for medium-sized cable robots with low travel speed and does not take into account the impact of cable elasticity. A simulation model was conducted and the results showed the advantages of this method in increasing the probability of convergence with small errors. The results of computation and experiment are analyzed to evaluate the effectiveness of the proposed model**

***Index Terms*—Cable robots, forward kinematics, inverse kinematics, cable sagging, ANFIS**

I. Introduction

In recent times, there are many large-sized cable robots was built and applied due to their advantages [1-3]. Cable Robots or Cable driven parallel robots (CDPRs) are a special type of robots with parallel structure, they are formed by replacing all of the hard links supported by cables, compared to traditional robots, these robots are well-suited to a variety of potential applications [4-5].

One of the complicated issues when designing and calculating the precise control of cable robots is the influence of cable sag, especially for large sized robots. P. Merlet [6] develops a mathematical model to analyze the singularity of the forward and reverse kinematics problem of cable robots taking into account cable sag of cable, based on Irvine's elastic catenary. The results show that both kinematic problems have singularities and these points are usually located at the boundary of the active space. The "elastic catenary" was developed by Irvine [7] used to simulate the cable lengths and then handle the inverse pose kinematics problem in this study. They also offered experimental validation, demonstrating that the elastic catenary equations and experimental results are in good accord. The difference between theoretical and experimental cable tension is also provided by Russell and Lardner [8] based on an experimental model of elastic catenary models. Dheerendra Sridhar and Robert L. Williams II [9] propose a method to investigate the differences in cable length errors and computation, comparing the straight - line cables assumption vs. a cable - sag model, the study and analysis of the effects of cable sag on the calculation of cable length in CDPRs has been conducted the primary goal of the research. The study also looked into the consequences of cable density, cable diameter, robot footprint size, and computational requirements. Yu Su, Yuanying Qiu, and Peng Liu [10] employ the proposed dynamic model and the sag-to-span ratio as constraint requirements to find the best model for distributing cable tensions of CDPR used for moving camera and driven by 4 cables. An optimization method is developed based on the ideal model to find the optimal solution satisfying the constrained conditions in an infinite number of possible solutions. M. Gouttefarde, J. Collard, N. Riehl and C. Baradat [11] presents a method to determine cable deflection based on parabolic and linearized Irvin models. From there, the cable length with sag was calculated by the linear relationship between the components to decrease the computation time. The model is only valid for cable robots with the same number of cables as degrees of freedom.

The cable can only work unilaterally under tension and without compression, which is a key feature of cable controllers. The CDPRs have many different classification methods. Robot cable can be classified according to the following requirements: m is the number of cables, while n is the number of degrees of freedom. Ming and Higuchi [12] proposed this kinematic categorization to distinguish between cable robots. In this

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paper, we modeled a CDPR has 3 DOF and driven by 4 cables that are fully constrained with $m=4$, $n=3$ and present the structure and inverse kinematic problem (IKP) of this robot. The sagging of cables base on tension force distribution was compute by algorithm method to create train data for configuring the ANFIS model, the ANFIS model is used to predict cable sag in its workspace that is only deflected by its own weight.

II. Inverse Kinematic of the 4 Cable Robots Taking Into Account Sagging of Cables

Fig. 1 illustrates the kinematic structure of the four cables CDPR, where P and A_i, $i = 1, 2, 3, 4$, are connecting points of the i^{th} cable attached to the moving point and four columns of the robot frame, respectively. Variable vectors l_1, l_2, l_3, l_4 denote the straight length of cables. Unlike the inverse kinematics problem (IPK) of rigid-linked robots, the IPK of cable robots consists of finding the theoretical cable lengths corresponding to a given moving point P simultaneous with solving the force distribution problem to find the cable tensions corresponding to static equilibrium, then calculate the length of the cable with sag with the cable tension and the length of cables respectively [8-11], straight -line cable length can be presented in vector form

$$\vec{l}_i = \overrightarrow{OP} - \overrightarrow{OA_i} \tag{1}$$

where $i = 1, 2, 3, 4$

The static equilibrium equation of this system can be present in $Oxyz$ as

$$\vec{F} + \sum_{i=1}^{4} \vec{\tau}_i = 0 \tag{2}$$

where F is the sum of external force acting on moving point, $\tau_i > 0$ are tension of cables.

In this case, the cable robot has 3 DOFs driven by 4 cables so redundant of system is 1, equation (2) becomes

$$\mathbf{F} + \mathbf{A\tau} = \mathbf{0} \tag{3}$$

where A is structure matrix of robot, $\boldsymbol{\tau} = [\tau_1\ \tau_2\ \tau_3\ \tau_4]^T$ is tension matrix. The structure matrix is given by

$$\mathbf{A} = \begin{bmatrix} \mathbf{u}_1 & \mathbf{u}_2 & \mathbf{u}_3 & \mathbf{u}_4 \end{bmatrix} \tag{4}$$

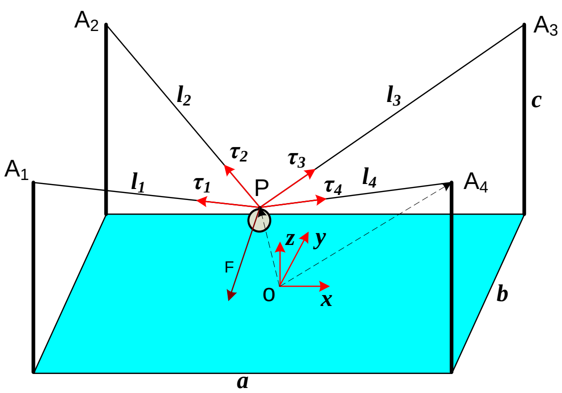

Figure 1. Cable robots with 4 sagging cables

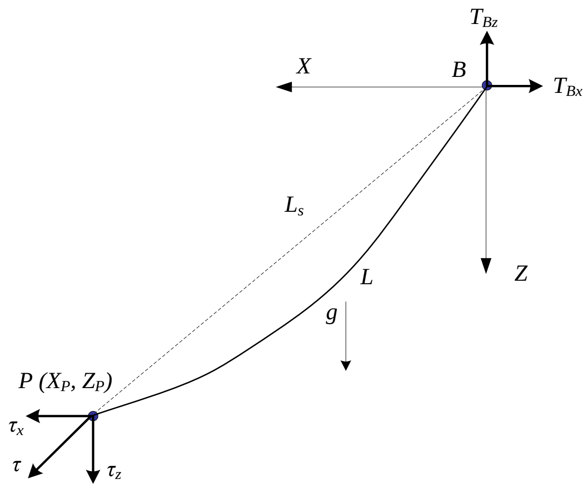

Figure 2. The cable model with sagging

where $\mathbf{u}_i = \begin{bmatrix} \frac{l_{ix}}{\|l_i\|} & \frac{l_{iy}}{\|l_i\|} & \frac{l_{iz}}{\|l_i\|} \end{bmatrix}^T$ is unit vector of cable i.

To calculate the corresponding sag cable length, Irvine's famous chain cable formula is applied [7-11], with the cable model between two points given in Fig.2, where A and P is connecting point of cables on base frame and end-effector of robot, L_S is the distance between A and P or the length of straight cable, L is the cable length from A to P taking into account the cable sagging, τ_x and τ_z are the components of tension τ on X and Z axis act on P, and (x_p, z_p) are the coordinates of the moving point, g is the gravity acceleration. The relationship between cable length with sagging, straight cable length and cable tension are simplified by the equation represented as follows.

$$x_p = \frac{|\tau_x|}{\rho_L g}\left[\sinh^{-1}\left(\frac{\tau_z}{\tau_x}\right) - \sinh^{-1}\left(\frac{\tau_z - \rho_L g L}{\tau_x}\right)\right] \tag{5}$$

$$z_p = \frac{1}{\rho_L g}\left[\sqrt{\tau_x^2 + \tau_z^2} - \sqrt{\tau_x^2 + (\tau_z - \rho_L g L)^2}\right] \tag{6}$$

Thus, to find the cable length taking into account the cable sagging, equations (1-6) must be solved simultaneously, this is a nonlinear system, which can be solved by numerical method. However, the long computation time is a problem that needs to be considered for cable robot control applications. Some studies have linearized the relationship of the components in this system to reduce computation time [11][13], however the results only apply to specific configurations.

In the next section, we use numerical methods to calculate the sag cable length in the entire workspace of robot, then combine the data to establish the ANFIS models used to predict the sag cable lengths for the configuration of cable robot above, then evaluate the accuracy of the results from the built model with numerical methods.

III. ANFIS Model for Predicting Sagging of Cable

ANFIS - Adaptive neuro-fuzzy inference system - is a combination algorithm between Fuzzy Inference system and artificial neural network, this combination takes advantage of two models: fuzzy logic allows easy system design, in then the neural network allows to learn what we ask of the controller [14-15]. It modifies functions dependent on shape, position and combination completely automatically. This reduces the time as well as the cost of system development. The ANFIS function creates a fuzzy inference system (FIS) utilizing the provided input/output data set, and its membership function parameters are changed using neural network training procedures such backpropagation or combine propagation with the least squares approach. As a result, our fuzzy system can "learn" from the data set. With the nonlinear relationship between input – moving point coordinates - and output - cable deflection shown in equations 1-6, the input-output nonlinear relationship in the fuzzy model needs to be built depends heavily on the fuzzy partitions of the input-output space. Therefore, determining the membership function in fuzzy models becomes very important. In fuzzy neural networks, this tuning can be considered as an optimization problem using learning algorithms to solve. By assuming the membership functions have a certain shape, then proceed to change the parameters of that shape through the process of learning by neural network. Thus, we need a data set in the form of desired input-output pairs for the neural network to learn and also need a table of initial rules based on those dependent functions.

In this study, a ANFIS model was developed for predicting cables sag of CDPR with 3DOF driven by 4 cables, the static workspace of robot was show in Fig.3. All training data for were collected on workspace of robot, i.e points that satisfy the equilibrium equation [8-11]. The Dual simplex Algorithm was used to calculate the cable tension for these locations under the condition that the sum of the cable strains is minimal, then the Trust-Region-Dogleg algorithm was used to determine the lengths of cables with the corresponding cable sagging [16].

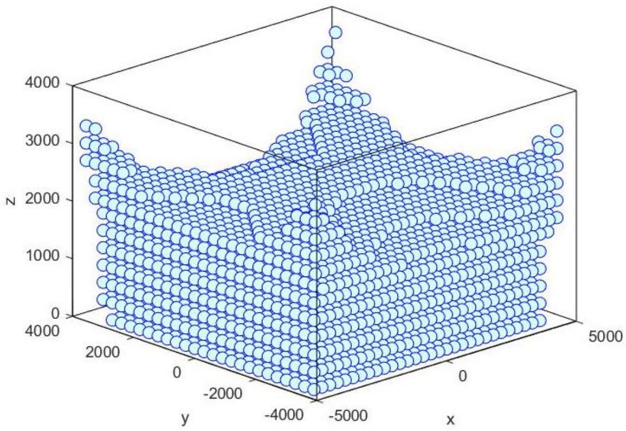

Figure 3. The workspace of 4 cables CDPR

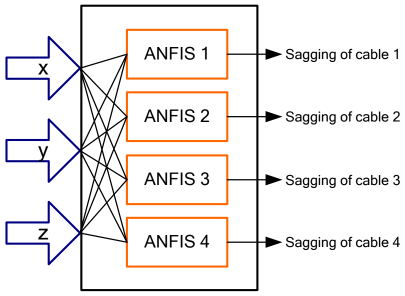

Figure 4. Proposed ANFIS architecture for cable sagging prediction

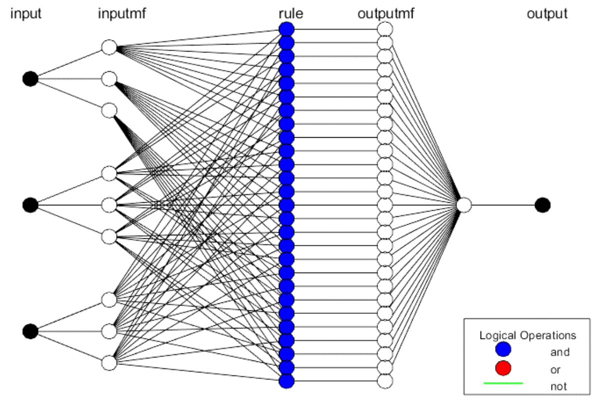

Figure 5. ANFIS structure for a cable

CDPR parameters are given in Table I and data of the IKP taking into account cable sagging are used for training ANFIS model, and also used to evaluate the accuracy of the model over the entire operating space. In the model with 3 inputs being the coordinates of the moving point and 4 outputs being the sagging of the 4 cables respectively, to predict the cable sags reported in this paper, a parallel ANFIS system is created. Fig.4 depicts a system made up of four parallel ANFIS models, each of which receives the moving point's location as input. A first-order Sugeno model with 27 rules and three generalized Gaussian membership functions is used to generate the ANFIS. The number of membership functions for each ANFIS was calculated through experimentation. The multi-layer feedforward adaptive network ANFIS structure phase $i(i=1,\ldots,4)$ is depicted in Fig.5. The CDPRs' position coordinates are described in the first layer, which has three inputs. The rule layer is the second layer, which calculates the firing strengths of each rule using the Product t-norm. After that, a layer of normalization is performed. The training rule option is the Levenberg–Marquard variation of the gradient backpropagation method. A single output layer reflects the sinking value of cable i in the final layer. Three hidden layers are involved in inverse kinematics of CDPRs that account for cable sag.

The first is the fuzzification layer, which uses Gaussian transfer functions to convert inputs to linguistic variables. When compared to normal back-propagation, this option provides for a significantly faster learning process with fewer iterations. ANFIS network with three Gaussian membership function and hybrid learning method is trained using the coordinates and sag of cables as training data. On the whole wrench feasible workspace of the CDPR, the training data of four ANFIS networks for sags of four cables were gathered. The ANFIS receives the coordinates as input and outputs the sag. Through a process known as training.

The membership functions will be changed during the training phase to decrease the error reach to the preset error or use up the preset epoch. ANFIS model will be fully established at the end of the training process, and it will be tested using the deduced inverse kinematics. Fig.6 show the response surface of 4 ANFIS model for predicting sagging of 4 cables of CDPR, ANFIS models were built with 3998 training data pairs and checked by 1001 data pairs, the result show that 4 surfaces have nearly the same shape, deviated at an angle of 90 degrees according to the wiring structure of the robot in the Fig.1. The correlation coefficients of four ANFIS models are greater than 0.9 and 0.934 for train data and test data respectively.

The histogram in Fig.7 shows the distribution of the calculation errors of the ANFIS model compared with the TRDA model, the errors vary between -20 mm to 20 mm, but the number of errors greater than 10(mm) is very small, the error mainly focuses from -5 to 2mm for all cables. Compared with cable lengths from 4700mm to 8700mm, this error is suitable for large-sized cable robots that are applied in tasks that do not require rigorous precision such as moving materials, controlling camera position in halls, stadiums. To evaluate the accuracy of this model, the following section will experiment on specific trajectories to analyze poses that cause large errors and propose options to improve the accuracy of the ANFIS model.

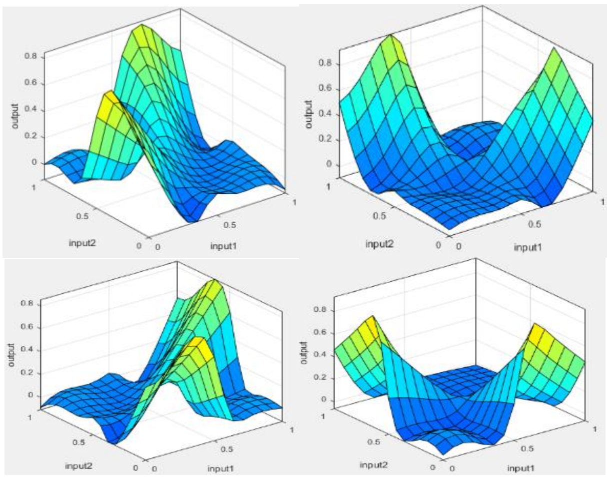

Figure 6. Response surface of ANFIS prediction system

TABLE I. SPECIFICATION OF CDPR

Input Variable	Symbol	Value
Frame Length	a (m)	8
Frame Width	b (m)	8
Frame Height	c (m)	4
End-effector mass	Me (kg)	100
Cable Diameter	Dc (mm)	8

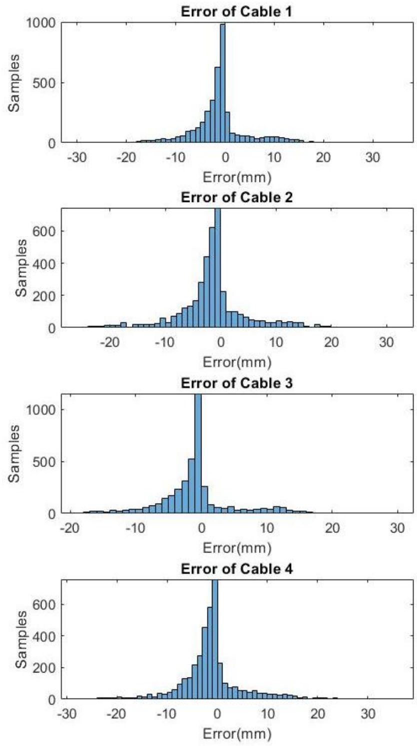

Figure 7. Response surface of ANFIS prediction system

IV. EXPERIMENTS AND DISCUSSIONS

To evaluate the responses of ANFIS models built for predicting sag of cables for CDPR with configuration as in Fig.1 and Table I, from the given trajectories, a computational program divides the trajectory into multi nodes for the robot to move, the nodes are checked to see if they belong to the robot's workspace, then calculate the distribution cable tension, cable sagging are calculated by two methods, which are TRDA and ANFIS, in which the input of the TRDA calculation method is the node positions and the corresponding cable tensions, while the ANFIS model only need information about the coordinates of the nodes, the cable sagging calculation results of the ANFIS models and the calculation method are performed on the same designed trajectory in the feasible workspace.

Fig.8 show the result of sagging, lengths and tensions of cables predicted by ANFIS and computation method – TRDA when robot moves along the closed curve path, the trajectory was calculated along a curve path following the equation (7), with the tension distribution method was used, the cable sagging depend on the cable length and cable tension respectively. Cable sagging is inversely proportional to cable tension and proportional to cable length, the cable sagging reaches to its maximum value about 60mm when cable length is about 8000 mm and cable tension is about 80N. cable sagging approaches its minimum values when cable tension is greater than 500N. The comparison results between the cable deflection obtained from the ANFIS model and the TRDA calculation method show that the error is very small, close to zero in the locations with high cable tension and small deflection and the cable tension and cable deflection changes continuously.

The maximum error of the prediction model occurs at the point where there is a sudden change of cable tension and cable deflection, the maximum error is about 40mm in this position.

$$\begin{cases} x = 2800.\sin t \\ y = 1500.\cos t \\ z = 1000 \end{cases} \tag{7}$$

Table II lists 11 node points randomly taken in the robot's workspace, the point-to-point trajectories are designed as linear motion between the nodes, the trajectory starts at point P1 and ends at P11 coincides with P1. The corresponding joint trajectory is depicted in Fig.9, the length of the driven cables is calculated along the moving trajectory of the nodes, respectively, the cable sagging is calculated by the two methods TRDA and ANFIS is illustrated in Fig.10, similar to the curve path, the errors predicted by the ANFIS model occur at locations where there is a sudden change in the magnitude of the cable tension, resulting in the nature continuity of the ANFIS model, so to improve the accuracy of the prediction model, it is necessary to make the cable tension change continuously using a suitable cable tension distribution model.

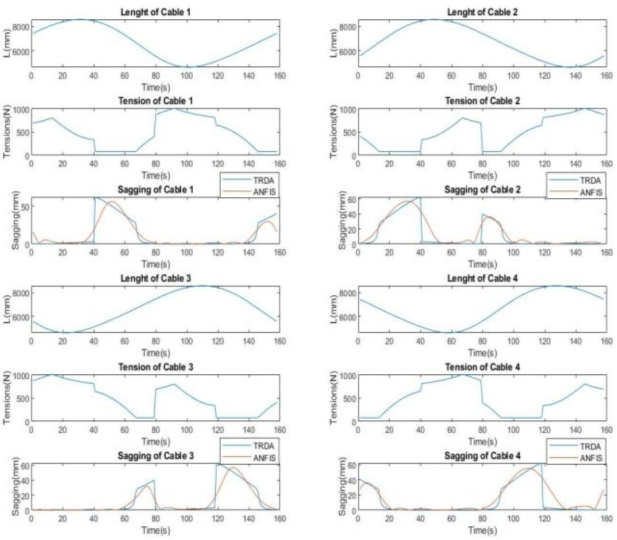

Figure 8. Sag of 4 cables along close-curve path

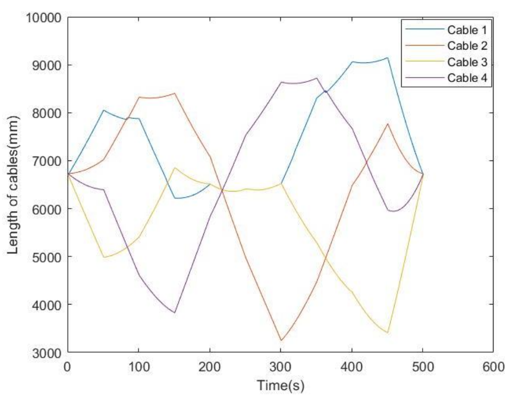

Figure 9. Length of 4 cables along linear path

TABLE II. COORDINATE OF NODE POINTS

Node points	Node points
P1(0, 0 ,400)	P7(-2000, 2000, 2400)
P2(1500, 1000, 900)	P8(-500, 3000, 1400)
P2(2500 , -500, 1400)	P9(1500, 2500, 900)
P4(1500, -2000, 1900)	P10(3000, 1500, 1900)
P5(500, -500, 900)	P11(0, 0, 400)
P6(-1000, 1000, 1400)	

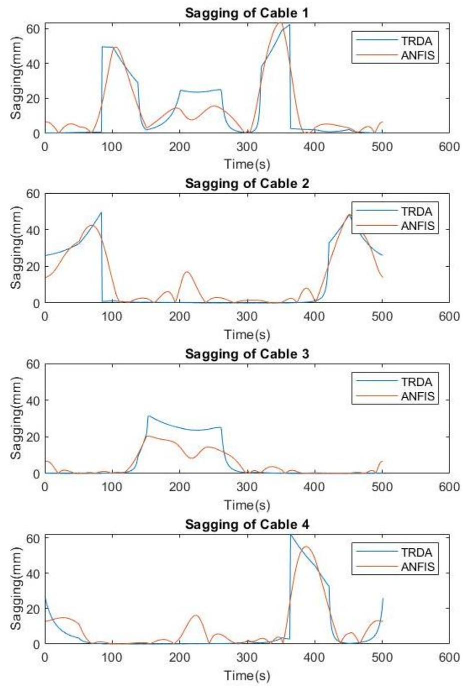

Figure 10. Sag of 4 cables along linear path

V. CONCLUSION

The results of this study show that the efficiency of using ANFIS model to estimate the cable sag of the large size cable robot. This result can be used to build a simple estimation model for specific cable robots, simplify the calculation process, with appropriate response for cable robot applications. The results of this paper are interesting because they solve a problem that no closed-form solution is known. Therefore, ANFIS can improve the accuracy of cable robots and explore high nonlinear functions and has been successfully applied to approximate complex mapping between robot positions and cable lengths. The results of the computation of this paper have demonstrated the advantages of this method in increasing the convergence with model accuracy which is superior to the corresponding methods for parallel cable robots. In the future works, a new method of cable tension distribution will be studied to generate continuous cable tensions along the operating trajectory, which may increase the accuracy of the ANFIS prediction model. The calculated results will be tested on CDPR (Fig.11) to evaluate the accuracy. The ANFIS model will also be designed and tested on different CDPR configurations, thereby having a more accurate assessment of the ability to use the ANFIS model in predicting the nonlinear noise components affecting the accuracy of CDPRs.

Figure 11. Cable robotic system in experiments.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

All authors contributed to conceptualization and design of the study structure and content. [Tuong Phuoc Tho] performed the document preparation, data collection; [Nguyen Truong Thinh] analyzed the results; the first draft of the manuscript was written by [Tuong Phuoc Tho]; all authors commented on previous versions of the manuscript; all authors had approved the final version.

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