RESEARCH ON APPLICATION OPTIMIZATION OF A CABLE-DRIVEN MONITORING CAMERA ROBOT SYSTEM FOR LOGISTICS WAREHOUSE

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The problems of the tension optimization and stability of a cable-driven monitoring camera robot (CDMCR) for logistics warehouse are studied in this paper. First, the configuration design of the CDMCR for the logistics warehouse was introduced. Secondly, the dynamic model of the CDMCR for logistics warehouse is established based on the Newton Euler equations. The tension optimization of the CDMCR was then studied using the minimum variance (MV) and the middle extremum (MIDE) method. The characteristics of different optimization algorithms were given by the simulation analysis. Finally, the current cable tension stability factors and global cable tension stability factors were defined, and a stability evaluation method was given through the weighted method. Through simulation calculation and stable workspace, the stability evaluation index of the CDMCR for logistics warehouse was verified. The result shows that the stability in the middle and upper area of the workspace for the CDMCR for logistics warehouse is better. The research results provide a foundation for the development of experimental prototypes and the research of intelligent control management methods.

Keywords: logistics warehouse, cable-driven monitoring camera robot, optimization methods, stability performance factors, stability margin.

1. Introduction

With the development of science and technology, modern logistics management also tends to be intelligent. It is of great significance to develop a new type of safety monitoring and management system for logistics and warehouse that can effectively manage warehouse staff, standardize operations, and improve the management level of logistics and warehouse. Generally, helicopters and crank-arm lift trucks are often used in space photographing. However, helicopters have some disadvantages, such as noise and their work are easily affected by the weather and so on. The working range of crank-arm lift trucks is small, which easily affects the normal operation and inventory of the

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warehouse. So, a new photographing and monitoring method that can achieve full scenes, real-time camera, work efficiency and good stability need to be studied, and the cable-driven parallel robots (CDPR) can perfectly meet the above requirements [1].

The CDPR is a special robot that the operated object is driven by the cables. Because the cable mass is light and the inertia is smaller, its working speed and acceleration are high, which effectively improves the working efficiency of the robot. In addition, it also has the following performance advantages: large workspace, high accuracy, large load capacity, strong reconfigurability, etc. [2-3], therefore, it can well meet the needs of monitoring camera management in logistics warehouse. The CDPR have been used in different fields, and different characteristics in different fields have been studied separately, for example, dynamics [4], system stiffness [5], workspace [6], control theory and so on [7]. Due to the redundancy of the CDPR, the value of the cable tension should be determined in real-time in practical applications to improve the efficiency of the system. Therefore, a lot of research on the cable tension optimization problem has been studied. The cable tension optimization problem was studied using minimum p-norm in the literature [8]. When $p \geqslant 3$, the minimum-norm optimization algorithm has feasible cable tension adjustment capabilities, but the calculation time is longer and the obtained cable tension volatility is larger [8]. The cable tension optimization of the CDPR was studied using the minimum 2-norm and Closed Form (CF) optimization algorithm, separately. The results show that the cable tension calculated by the minimum 2-norm is smaller on the whole, and the tension adjustment ability is limited. The real-time of the CF method is fast, but the cable tension adjustment can be limited [9]. Therefore, the optimization problem of cable tension needs to be further study.

The stability of the CDPR is an important performance index for CDPR system, but the stability evaluation of CDPR has not formed a theoretical system, but some studies have carried out to evaluate the stability of this type of robot. *Wang et al*. studied the stability evaluation method of the CDPR by using Krasovsky method[10], but this method can only determine whether the system is stable. *Carricato et al*. proposed a static stability evaluation model using the Hessian matrix, which can evaluate whether the system is stable by the eigenvalues of the Hessian matrix[11-12]. The system stiffness of the CDPR is a crucial factor in assessing the performance and stability of the CDPR[13]. *Bosscher et al*. proposed a quantitative evaluation method based on the motion screw[14]. A stability evaluation method was proposed based on the full stiffness matrix theorem[15], but the mathematical model established is complicated and the calculation time is long, which is difficult to use in real-time in practical applications. In the CDPR, the motion of the operated object can be realized under the action of the tension applied by the cables. Therefore, combined with the basic theory of system stability, it is of practical physical significance to study the stability index according to the cable tension characteristics.

The stability of the CDMCR for logistics warehouse is of great significance to the normal operation of the system and the quality of the captured image data. Therefore, the practical application problems of cable tension optimization and stability of the CDMCR for logistics warehouse were studied in this paper. The other content of this paper is arranged as follows: in the second section, the configuration of the CDMCR for logistics warehouse is introduced. Based on the dynamic model of the CDMCR system, the optimization methods of cable tensions are analyzed in the third section. The stability evaluation of CDMCR for logistics warehouse is discussed in the fourth section. Finally, the research conclusions of this paper are given in the fifth section.

2. CDMCR for the logistics warehouse

The designed CDMCR for logistics warehouse is a special CDPR whose end-effector is driven by cables to complete the camera task, as shown in Fig. 1. It consists of a three-degree-of-freedom camera moving platform, four groups of cable drive units and a control center. The cable drive unit consists of a motor, a fixed pulley and cable. Each pulley is installed on the top of the mast, and one end of the cable is fixed on the camera moving platform, the other end is fixed on the traction wheel of the motor through the fixed pulley. The traction wheel is driven by the servo motor installed on the frame to realize the extension and contraction movement of the cable. The monitoring and camera tasks of the camera platform can be realized by the control of four groups of cables.

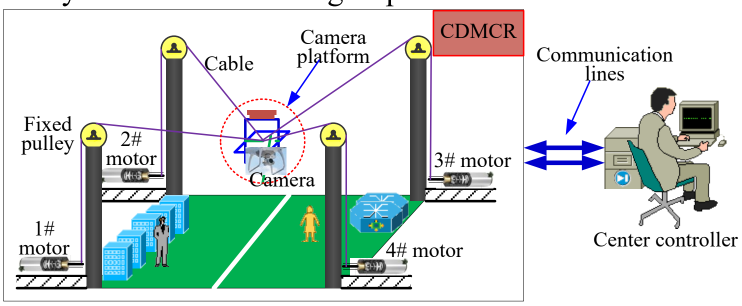


Fig. 1. CDMCR for the logistics warehouse

According to the task needs, man can directly give the location of the camera to reach, based on the motion trajectory of the task trajectory planning, the acceleration of the camera in the process of movement can be calculated, and then the force F can be calculated. Finally, combined with the cables tension optimization algorithm, the optimized tensions of four cables can be calculated in real time. Based on the control algorithm and the optimized tensions of four cables can be converted into control commands, which will be sent to the drivers, and the drivers drive the motors to output the corresponding torque to achieve real-time control of the tensions of four cables.

3. Analysis of dynamics and cable tension optimization

3.1. Dynamics modeling

In the CDPR, the robot size and cable mass are small, so the cable deflection caused by the cable's own weight can be negligible. The cable can be regarded as a straight line. The kinematics model of the CDMCR for logistics warehouse established is shown in Fig. 2. *O-XYZ* represents the global coordinate system. b_i (i =1,2,3,4) represents the position of the fixed pulley. L_i represents the cable length between the camera P and the fixed pulley b_i. The position of the camera P in *O-XYZ* is noted as (x, y, z), and the position of the fixed pullet b_i in *O-XYZ* is noted as (x_i, y_i, z_i).

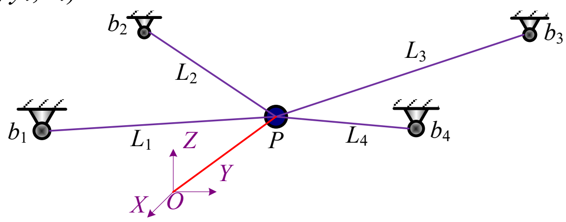


Fig. 2. Kinematic model of CDMCR for the logistics warehouse

It can be seen from Fig. 2 that the length of the cable is:

$$\boldsymbol{L}_i = \boldsymbol{Ob}_i - \boldsymbol{OP} \tag{1}$$

According to Newton-Euler, the static mechanical balance equation of the CDMCR for logistics warehouse can be expressed as:

$$\boldsymbol{J}^{\mathrm{T}}\boldsymbol{T} = \boldsymbol{F} \tag{2}$$

$$\boldsymbol{T}_{\min} \leqslant \boldsymbol{T} \leqslant \boldsymbol{T}_{\max} \tag{3}$$

Where $\boldsymbol{T} = \begin{bmatrix} t_1 & t_2 & t_3 & t_4 \end{bmatrix}^{\mathrm{T}}$ is the cable tension vector. The lower bound of cable tension is $\boldsymbol{T}_{\min} = \begin{bmatrix} t_{1,\min} & t_{2,\min} & t_{3,\min} & t_{4,\min} \end{bmatrix}^{\mathrm{T}}$ and the upper bound of cable tension is $\boldsymbol{T}_{\max} = \begin{bmatrix} t_{1,\max} & t_{2,\max} & t_{3,\max} & t_{4,\max} \end{bmatrix}^{\mathrm{T}}$. $\boldsymbol{F}$ is the force acting on the camera P, $\boldsymbol{F} = m\ddot{\boldsymbol{P}} - m\boldsymbol{g}$,where $\ddot{\boldsymbol{P}} = (\ddot{x}, \ddot{y}, \ddot{z})$. $m\boldsymbol{g}$ is of the gravity of the camera. The structure matrix of the CDMCR for logistics warehouse is $\boldsymbol{J}^{\mathrm{T}}$.

It can be seen from the vector closure principle that the CDMCR for logistics warehouse satisfies the vector closure principle. The matrix $\boldsymbol{J}^{\mathrm{T}}$ is not a square matrix. Therefore, the tension $\boldsymbol{T}$ can be solved using the matrix generalized inverse theory:

$$\boldsymbol{T} = \boldsymbol{T}_s + \boldsymbol{T}_n = \boldsymbol{J}^{+}\boldsymbol{F} + \boldsymbol{\lambda} \cdot \boldsymbol{N}(\boldsymbol{J}^{\mathrm{T}}) \tag{4}$$

Where $\boldsymbol{J}^{+} = \boldsymbol{J}^{\mathrm{T}}(\boldsymbol{J}\boldsymbol{J}^{\mathrm{T}})^{-1}$ is the generalized inverse matrix of $\boldsymbol{J}^{\mathrm{T}}$. $\boldsymbol{N}(\boldsymbol{J}^{\mathrm{T}})$ is the zero-space vector of $\boldsymbol{J}^{\mathrm{T}}$. $\boldsymbol{T}_s$ and $\boldsymbol{T}_n$ are the special solution and the general solution of Eq.(2), respective. Since the CDMCR for the logistics warehouse meets n=m+1(n and m are degrees of freedom and number of cables of the CDMCR for the logistics warehouse, separately), λ is an arbitrary scalar.

The convex combination of the lower bound λ_l and the upper bound λ_h is represented by λ^c, then the Eq.(4) will be rewritten as follows:

$$\boldsymbol{T} = \boldsymbol{J}^{+}\boldsymbol{F} + \lambda^{c} \cdot \boldsymbol{N}(\boldsymbol{J}^{\mathrm{T}}) \tag{5}$$

3.2. Optimization analysis of cable tensions

Combined with the above discussion, the value range of λ is:

$$\lambda_l \leqslant \lambda \leqslant \lambda_h \tag{6}$$

$$\begin{cases} \lambda_l = \max\limits_{1\leqslant i\leqslant 4}\left\{ \min\limits_{1\leqslant i\leqslant 4}\left(\dfrac{t_{i,\min} - t_{s,i}}{\boldsymbol{N}_i(\boldsymbol{J}^{\mathrm{T}})}, \dfrac{t_{i,\max} - t_{s,i}}{\boldsymbol{N}_i(\boldsymbol{J}^{\mathrm{T}})} \right) \right\} \\ \lambda_h = \min\limits_{1\leqslant i\leqslant 4}\left\{ \max\limits_{1\leqslant i\leqslant 4}\left(\dfrac{t_{i,\min} - t_{s,i}}{\boldsymbol{N}_i(\boldsymbol{J}^{\mathrm{T}})}, \dfrac{t_{i,\max} - t_{s,i}}{\boldsymbol{N}_i(\boldsymbol{J}^{\mathrm{T}})} \right) \right\} \end{cases} \tag{7}$$

Eq. (6) is the linear constraint condition about λ. The λ will cause the non-uniqueness of $\boldsymbol{T}_n$. Therefore, the distribution of $\boldsymbol{T}$ should be further adjusted through the selection of optimized value λ. Therefore, under constraint conditions, the optimization of cable tensions can be converted to an optimization problem about λ.

The cable tension optimization model of the CDMCR for logistics warehouse is:

$$\begin{cases} \min f(\lambda) \\ s.t.\ \ \boldsymbol{J}^{\mathrm{T}}\boldsymbol{T} = \boldsymbol{F} \\ \qquad \lambda_l \leqslant \lambda \leqslant \lambda_h \end{cases} \tag{8}$$

Where $f(\lambda)$ is the optimization objective function. Since the uniformity of the cable tension distribution of the CDMCR for logistics warehouse has a positive effect on the motion stability of the camera, the minimum variance and the MIDE optimization algorithms are used to optimize the cable tension in this paper. The feasible region of the optimization objective function is a one-dimensional array, hence the cable tension optimized by optimization algorithms is the optimal solution.

(1) *MV optimization algorithm*

When the *MV* of the tensions is used for optimization objective function, which can be expressed as:

$$f(\lambda) = \frac{1}{4}\left[\sum_{i=1}^{4}\left(t_i - E(t)\right)^2\right] \tag{9}$$

Where $E(t) = \left(\sum_{i=1}^{4}(t_{s,i} + n_i\lambda)\right)\Big/4$, let:

$$\begin{cases} f = \dfrac{1}{4}\left[\sum_{i=1}^{4}\left(t_i - E(t)\right)^2\right] \\ L = t_{s,1} + t_{s,2} + t_{s,3} + t_{s,4}, \qquad N = n_1 + n_2 + n_3 + n_4 \\ S = t_{s,1}{}^2 + t_{s,2}{}^2 + t_{s,3}{}^2 + t_{s,4}{}^2, \quad Q = n_1{}^2 + n_2{}^2 + n_3{}^2 + n_4{}^2 \end{cases} \tag{10}$$

Eq. (9) can be further expressed as:

$$f = A\lambda^2 + B\lambda + C \tag{11}$$

Where $A = \frac{Q}{4} - \frac{N^2}{16}$, $B = -\frac{LN}{8}$, and $C = \frac{S}{4} - \frac{L^2}{16}$.

The above analysis shows that $A > 0$, the objective function has a minimum value, and $\frac{\partial f}{\partial \lambda} = 2A\lambda + B$, let $\frac{\partial f}{\partial \lambda} = 0$, then $\lambda = -\frac{B}{2A}$. So there are three situations at this time:

(a) When $\lambda_l \leqslant \lambda \leqslant \lambda_h$, $\lambda^c = \lambda$, $\boldsymbol{T}$ can be expressed as:

$$\boldsymbol{T} = \boldsymbol{T}_s + \lambda^c \cdot \boldsymbol{N}(\boldsymbol{J}^{\mathrm{T}}) \tag{12}$$

(b) When $\lambda < \lambda_l$, $\lambda^c = \lambda_l$, $\boldsymbol{T}$ can be expressed as:

$$\boldsymbol{T} = \boldsymbol{T}_s + \lambda^c \cdot \boldsymbol{N}(\boldsymbol{J}^{\mathrm{T}}) = \boldsymbol{T}_{\min} \tag{13}$$

(c) When $\lambda > \lambda_h$, $\lambda^c = \lambda_h$, $\boldsymbol{T}$ can be expressed as:

$$\boldsymbol{T} = \boldsymbol{T}_s + \lambda^c \cdot \boldsymbol{N}(\boldsymbol{J}^{\mathrm{T}}) = \boldsymbol{T}_{\max} \tag{14}$$

According to the magnitude relationship among λ, λ_l and λ_h, the optimized cable tension can be directly calculated using the analytical expressions given in Eq.(12), Eq.(13) and Eq.(14).

(2) *MIDE optimization algorithm*

In MIDE optimization algorithm, let the general solution $\boldsymbol{T}_n$ be:

$$\boldsymbol{T}_n = \frac{\boldsymbol{T}_{\min} + \boldsymbol{T}_{\max}}{2} \tag{15}$$

The mechanical equation (2) of the CDMCR for logistics warehouse can be arranged as:

$$\boldsymbol{J}^{\mathrm{T}}(\boldsymbol{T}_s + \boldsymbol{T}_n) = \boldsymbol{F} \tag{16}$$

So,

$$\boldsymbol{T}_s = \boldsymbol{J}^{+}(\boldsymbol{F} - \boldsymbol{J}^{\mathrm{T}}\boldsymbol{T}_n) \tag{17}$$

According to Eq. (17) and Eq. (4), the optimized tension $\boldsymbol{T}$ is:

$$\boldsymbol{T} = \boldsymbol{T}_n + \boldsymbol{J}^{+}(\boldsymbol{F} - \boldsymbol{J}^{\mathrm{T}}\boldsymbol{T}_n) \tag{18}$$

So, the optimized cable tension can be directly calculated using the analytical expressions given in Eq.(18).

In order to analyze the cable tension characteristics obtained by the two optimization algorithms to improve the stability of the CDMCR for logistics warehouse and obtain good shooting image data, a case simulation is performed. The parameters of the CDMCR for logistics warehouse are as follows: b_1(50, 0, 20)m, b_2(0, 0, 20)m, b_3(0, 100, 20)m, b_4(50, 100, 20)m, the mass of the camera moving platform m=15kg. The lower bound of cable tension is $[15, 15, 15, 15]^T$ N, and the upper bound of cable tension is $[2500, 2500, 2500, 2500]^T$ N.

The desired trajectory of camera is shown as Eq. (19) :

$$\begin{cases} (x-x_0)^2+(y-y_0)^2=r^2 \\ r=r_0+\gamma t \\ z=z_0+kt \end{cases} \tag{19}$$

It can be seen from Eq. (19) that the desired trajectory is an ascending spiral with a gradually increasing radius, where (x_0, y_0, z_0)=(25,50,2)m, r_0=1m, γ=1, k=0.05. Based on the dynamic equations, desired trajectory of camera, and the structural parameters of the CDMCR for logistics warehouse, the cable tension calculation program for the desired trajectory was developed using MATLAB software. The calculation results are shown in Figs. 3-4. The desired trajectory of camera is shown in Fig. 3.

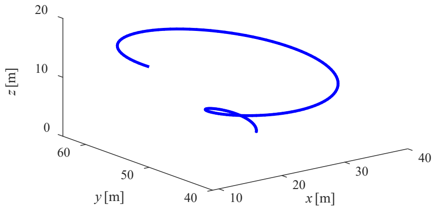
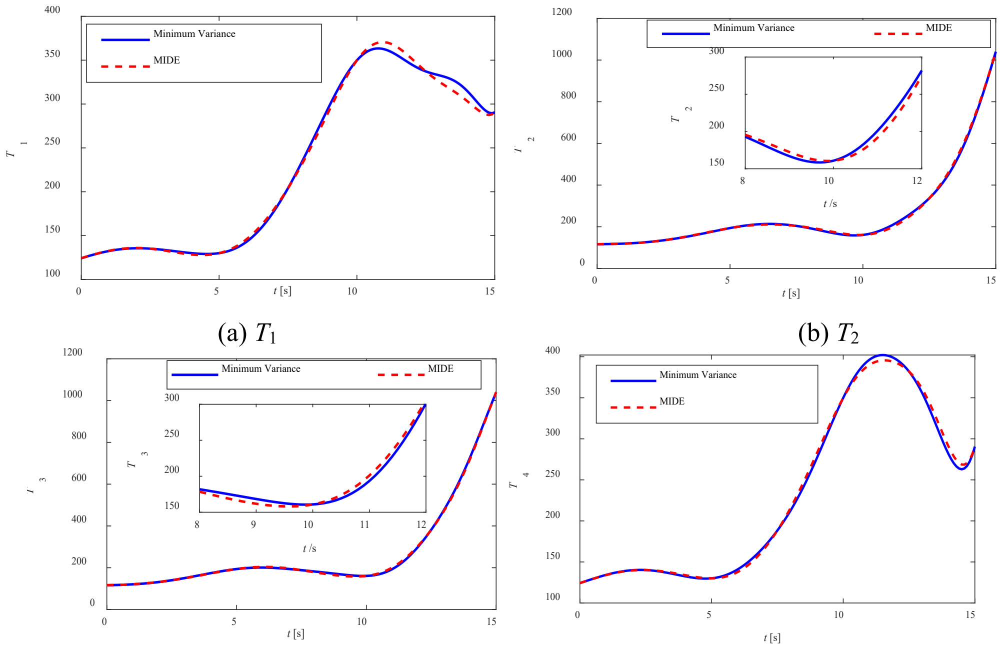


Fig. 3. The desired trajectory of camera

The cable tensions calculated by the above methods are shown in Fig. 4. It can be seen that when the camera moves according to the desired trajectory, the changes of the cable tensions obtained by the two optimization algorithms are basically the same. It is worth noting that the fluctuation amplitude of the tension T_1 calculated by the minimum variance optimization algorithm is larger than that of the tension T_1 calculated by the MIDE optimization algorithm during 10-15s. But the change curves are still smooth. In addition, the consumed time is 0.2120s using the minimum variance optimization algorithm and is 0.1630s using the MIDE optimization algorithm. The calculation speed of the MIDE optimization algorithm is fast and the obtained cable tension is less volatile.

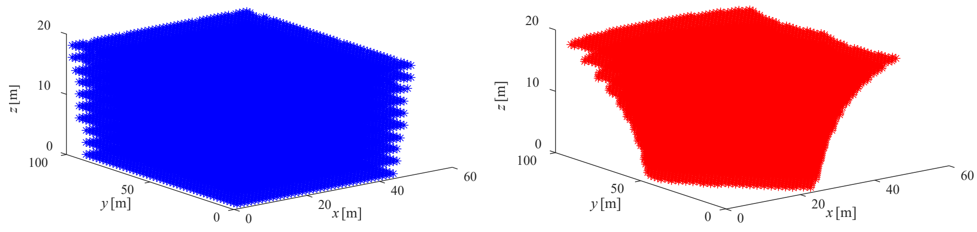


(a) T_1 (b) T_2

(c) T_3 (d) T_4

Fig. 4. The change curves of cable tensions

Based on the above cable tension optimization algorithms and the calculation program written in MATLAB, the workspaces of the CDMCR for logistics warehouse obtained with the above two optimization algorithms are shown in Fig. 5. The workspace of the CDMCR for logistics warehouse gradually increases from the bottom to the upper area, but the volume size of the workspace obtained by the MIDE algorithm is smaller than the volume of the workspace obtained by the minimum variance optimization algorithm. This is because the MIDE optimization algorithm only records the positions that meet the requirements, and the adjustment ability of the cable tension is poor, while the minimum variance optimization algorithm can adjust the cable tension in real-time through adjustment of scalar λ to meet the requirements. Therefore, the minimum variance optimization algorithm has a stronger adjustment ability of the tension.



(a) Minimum variance (b) MIDE

Fig. 5. The workspace in different optimization algorithms

In order to meet the full-range scene camera requirements of the CDMCR for logistics warehouse, this paper adopts the minimum variance optimization algorithm to calculate the cable tension.

4. Stability analysis

Stability is a prerequisite for the normal operation of the robot and an important prerequisite of ensuring the quality of the images captured by the CDMCR for logistics warehouse. However, the stability of the CDPR is difficult to evaluate using traditional stability methods. Hence, the stability of CDMCR for logistics warehouse should be studied.

Definition of the stability of the CDMCR for logistics warehouse: when the system is disturbed by the external interference, if the CDMCR for logistics warehouse can maintain the desired motion state, then the CDMCR system for logistics warehouse is stable. Where the external interference refers to the camera is subjected to the unexpected interference force form the outside system when the robot system normal movement, such as: wind, collision force. In other words, when the CDMCR system for logistics warehouse is subjected to external forces, the camera can stay at a desired position, and the CDMCR for logistics warehouse can be considered as stable.

Combined with the definition of the stability, it can be seen that when the more uniform distribution of restraining force on end-effector is and the larger restraining force is, the more difficult it is for the external force to change the state of end-effector, and the better the stability of the system is. Therefore, in the CDMCR for logistics warehouse, the more uniform distribution of the tension is and the lager the tensions are, the more difficult it is for external interference to change the motion state of the camera, that is to say, the stability of the CDMCR for logistics warehouse is better. Based on this, the stability performance factors and stability evaluation index of the CDMCR system for logistics warehouse are defined.

In order to appraise the uniformity of the distribution of the cable tensions at the one position and in the workspace, the current stable factor S_C and the global stable factor S_W are defined:

$$\begin{cases} S_C = T_{\mathrm{P,min}} / T_{\mathrm{P,max}} \\ S_W = T_{\mathrm{P,min}} / T_{\mathrm{P,min}}^{\max} \end{cases} \tag{20}$$

Where $T_{\mathrm{P,min}}$ and $T_{\mathrm{P,max}}$ are minimum and maximum cable tension at the current position, respectively. $T_{\mathrm{P,min}}^{\max}$ is maximum value of $T_{\mathrm{P,min}}$ in workspace.

On the basis of the above stability performance factors, *S* of the CDMCR for logistics warehouse is defined using the weighted method in this paper. The *S* can be used to measure the stability of CDMCR for logistics warehouse. Therefore, the stability evaluation index *S* can also be called the stability margin of the CDMCR, which can be expressed as:

$$S = \alpha S_C + \beta S_W \tag{21}$$

Where α and β are the weight coefficients of the corresponding stability factor, and $\alpha+\beta=1$.

In this paper, the configuration of the studied CDMCR for logistics warehouse is determined. Therefore, the size of the weight coefficients mainly depends on the importance and contribution of the corresponding stability factors to the stability of CDMCR for logistics warehouse. The current stability factor S_C directly reflects the constraints of the cable on the camera at the any position, and the global stability factor S_W reflects the uniformity of $T_{\mathrm{P,min}}$ in the workspace. The ability to resist and balance interference at the current position can directly reflect whether the CDMCR for logistics warehouse can capture good image data. Hence, the contribution of current stability performance factor S_C to the stability of the CDMCR for logistics warehouse is important than that of the global stability performance factor S_W. Therefore, the weight coefficients satisfy $\alpha>\beta$, combined with the structural characteristics of the CDMCR for logistics warehouse, we choose $\alpha=0.6$, $\beta=0.4$ in this study.

To sum up, the larger the current stability factor S_C is, the more even the size of the tensions is, which indicates the constraint of the tension on the camera at the current position will be more even, and the better the CDMCR's stability will be. The larger the global stability factor S_W is, the more uniform the tensions in the workspace is. The more concentrated the tension distribution is, that is, the larger the cable tension acting on the camera, the better the stability of the CDMCR for logistics warehouse. The larger the stability performance factors S_C and S_W are, the better the stability of the CDMCR for logistics warehouse is.

The flow diagram of the stability calculation for the CDMCR is shown as Fig. 6. According to the stability calculation flowchart, a calculation program for stability S, current stability factor S_C, and global stability factor S_W were written using MATLAB software. The calculation results are shown in Figs. 7-10, and the specific analysis is as follows.

We can see from Fig. 7 that the current stability factor S_C is distributed about the center position in the horizontal and vertical sections. Fig. 7(a) and 7(b) show that the S_C value gradually increases as the position high of the camera increases, especially at the boundary. In addition, the S_C value in the central of the horizontal plane is larger than that of in the boundary area.

Fig. 7(c) and 7(d) show that the S_C value is larger in the central of the vertical plane than that of the boundary, and the S_C value also gradually increases with the increase of the Z value, but the increase is not obvious on the section Y=50m.

In summary, the S_C is larger in the center and upper areas of workspace of the CDMCR for logistics warehouse.

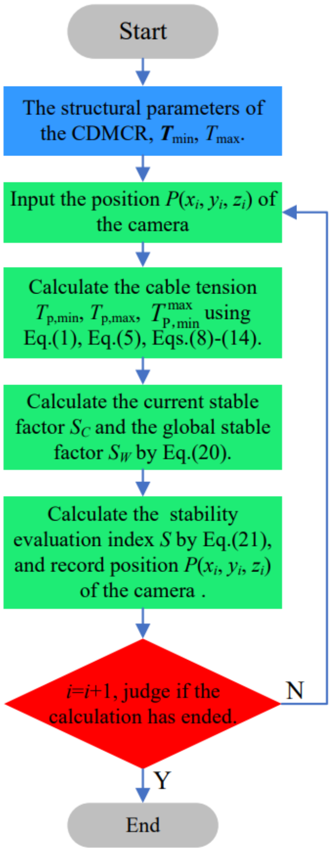
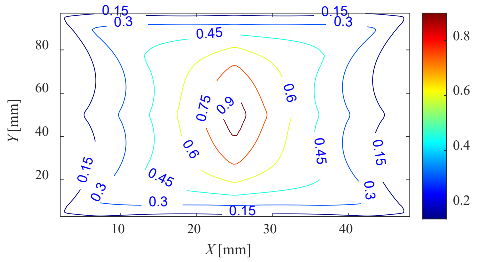
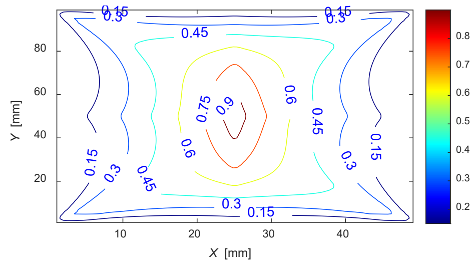


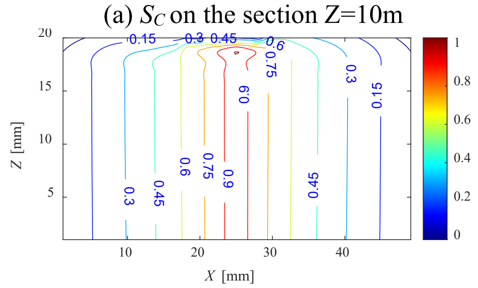
Fig. 6. The flow diagram of the stability calculation for the CDMCR



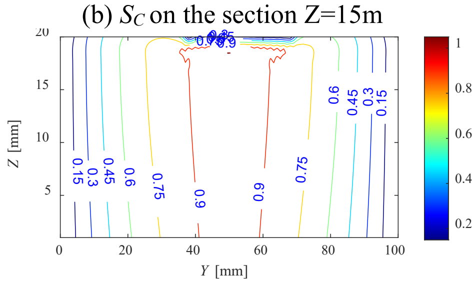
(a) S_C on the section Z=10m



(b) S_C on the section Z=15m



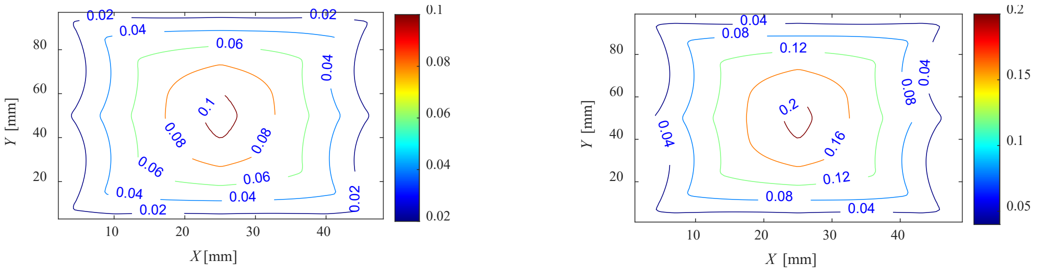
(c) S_C on the section Y=50m



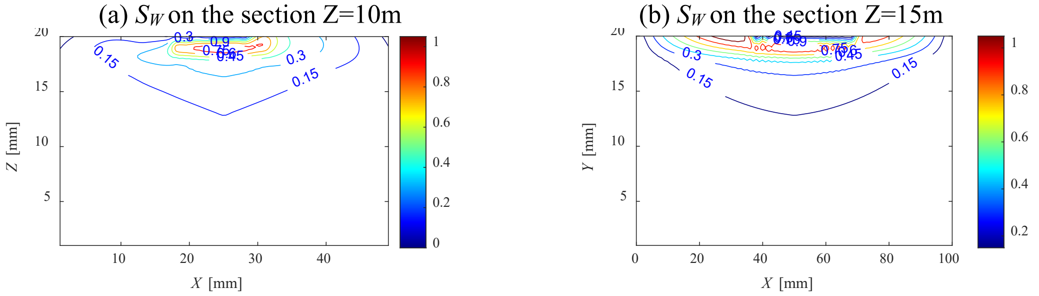
(d) S_C on the section X=25m

Fig. 7. The current stability factor S_C in different sections

We can see from Fig. 8 that global stability factor S_W is distributed about the center position in the horizontal and vertical sections. Fig. 8(a) and 8(b) that the S_W value increases significantly as the position high of the camera increases. In addition, the S_W value of the central in the horizontal plane is larger than that of in the boundary.



(a) S_W on the section Z=10m (b) S_W on the section Z=15m



(c) S_W on the section Y=50m (d) S_W on the section X=25m

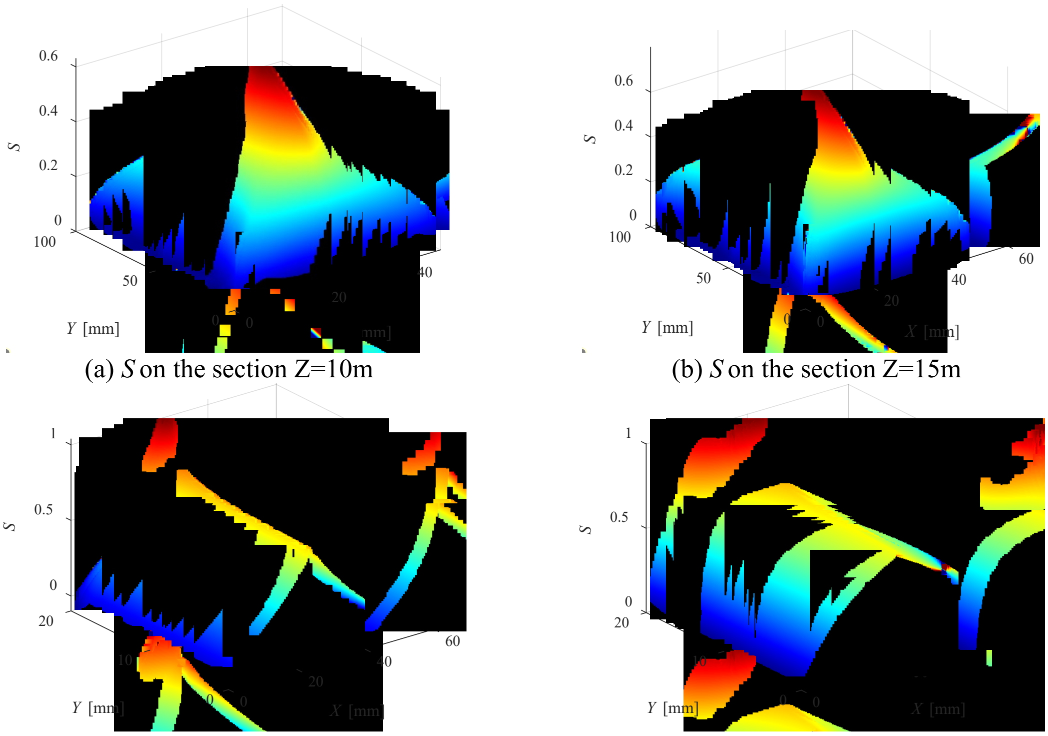
Fig. 8. The global stability factor S_W in different sections

Fig. 8(c) and 8(d) that the value S_W in the central of the vertical plane is larger than the boundary, and the value S_W is gradually increasing with the increase of Z. The increasing speed on the section Y=50m is smaller than that on the section X=25m.

In summary, S_W is larger in the central and upper areas of workspace of the CDMCR for logistics warehouse.

The stability margin S of the CDMCR for logistics warehouse on different sections is shown in Fig. 9. One can be seen from Fig. 9(a) and 9(b) that S is gradually increasing with the increase of the Z value in the horizontal section. And the increase in the boundary area is more obvious. In addition, the S value gradually decreases from the central area to the boundary of the horizontal interface.

One can know from Fig. 9(c) and 9(d) that the value S gradually decreases from the vertical center area to the boundary area in the vertical plane, and increases with the increase of Z. It is worth noting that the S value is increased significantly in the central upper area on the vertical section.



(a) *S* on the section Z=10m   (b) *S* on the section Z=15m

(c) *S* on the section Y=50m   (d) *S* on the section X=25m

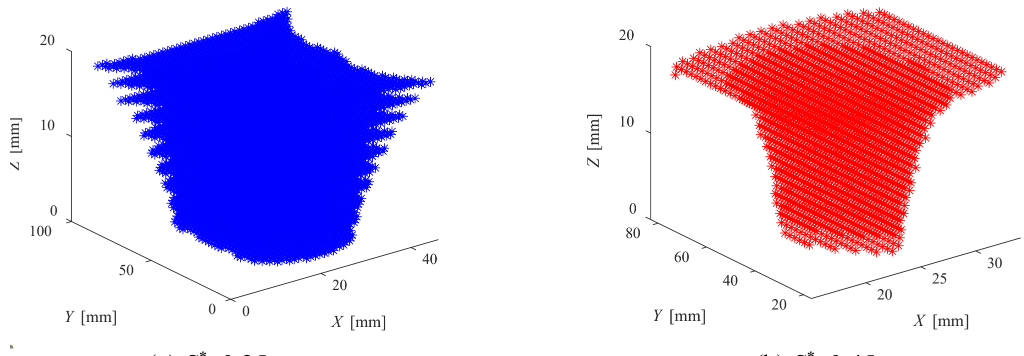
Fig. 9. The stability margin *S* in different sections

In Fig. 7 to 9, the value *S* gradually decreases to 0 in the boundary of the workspace, which indicates that the system is unstable in the boundary of the workspace when $S=0$.

In summary, *S* is larger in the upper and middle areas of workspace of the CDMCR for logistics warehouse, that is, the stability is better, so the quality of the captured image data will be better.

It can be seen from the definition of *S* that $S\in(0,1]$, the workspace with stability margin satisfying the condition $S\geq S^*$ can be defined as the stable workspace of the CDMCR for logistics warehouse. The value S^* of the stability index can be determined based on the requirements of different application scenarios. The stable workspace when $S^*=0.25$ and $S^*=0.45$ are shown in Fig. 10, when S^* increases, the volume of the stable workspace decreases, especially at the lower and boundary regions of the workspace. The stable workspace also proves that the stability is better in the middle and upper regions of workspace of the CDMCR for logistics warehouse than that of in the lower and boundary regions.

Based on the above discussion, one can see that stability of the CDMCR for logistics warehouse is better in the upper and middle regions of workspace, which meets the requirements of CDMCR for logistics warehouse on the whole.



(a) S^*=0.25 (b) S^*=0.45

Fig. 10. The stable workspace in different conditions

5. Conclusions

The practical application problems of tension optimization and stability of the CDMCR for logistics warehouse were studied in this paper. Based on the dynamics established of the CDMCR for logistics warehouse, the optimization problem of cable tension was studied using the minimum variance and MIDE optimization algorithm. The stability margin of the CDMCR for logistics warehouse was defined. One can know from the study results that the minimum variance optimization algorithm has stronger tension adjustment ability, but there is cable tension fluctuation. The MIDE optimization algorithm has fast calculation speed and poor cable tension adjustment ability. In addition, the CDMCR for logistics warehouse has better stability in the upper part of the workspace. It provides a basis for the subsequent development of experimental prototypes and the research of safety and intelligent control methods. Based on the stability evaluation index S， combined with factors such as system stiffness and change rate of cable tensions， the safety of the CDMCR for logistics warehouse will be studied, and the safety of the CDMCR for logistics warehouse will be also considered in the control method.

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