ANALYSIS OF WORKSPACE OF CABLE-TYPING CLOSE-COUPLING MULTI-ROBOT COLLABORATIVELY TOWING SYSTEM

Yanlin WANG [1], Zhigang ZHAO [2], Jinsong LI [3], Gang JI [4]

The paper presented the workspace of the cable-typing close-coupling multi-robot collaboratively towing system(CTMRTS). *The towing system was divided into three types of systems by different driving configuration. The generalized dynamic model of system was established by using Newton-Euler method, and its workspace was analyzed. Optimal solution of the cables tension was given by minimal norm least square method. Finally, parameters of the practical system were given, numerical simulation and analysis of the workspaces of three types of systems were given. The results show that the theoretical analysis is right, volume size and inclusion relationships of the workspaces of three types of systems are given. The results have provided a foundation for further research on optimization of system performance and the actual control of towing system.*

Keywords: towing system, multi-robots system, close-coupling, generalized dynamic model, workspace analysis

1. Introduction

The cable-typing close-coupling multi-robot collaboratively towing system(CTMRTS) has many advantages, such as its simple structure, large workspace and high precision, high load capacity and movement speed, high degree of modularity and work efficiency[1-3] and so on. In practical applications, CTMRTS plays an important role, therefore, the study of the system has great theoretical and practical application value.

Ming et al. [4] firstly proposed that the cable-typing parallel robot is divided into two categories: (1) when $m \le n$, it is the incompletely restrained positioning mechanism (IRPM). Where m is the number of cables, n is the

[1] School of Mechatronic Engineering, Lanzhou Jiaotong University, Lanzhou, China, e-mail:wangyanlin11@gmail.com
[2] Prof., School of Mechatronic Engineering, Lanzhou Jiaotong University, Lanzhou, China. e-mail:flapping@21cn.com.
[3] Senior Engineer, School of Mechatronic Engineering, Shanghai Jiaotong University, Lanzhou, China. e-mail: ljs@sjtu.edu.cn
[4] Senior Engineer, School of Mechatronic Engineering, Shanghai Jiaotong University, Lanzhou, China. e-mail: jgang@sjtu.edu.cn

number of degrees of freedom (DOF) for the towed object, the same below. (2) When m≥1+n, it is the completely restrained positioning mechanism (CRPM). Because of less constraints, when m<n, this kind of research are relatively few. Bin ZI et al. [5-8] have researched the dynamics, workspace and control system of the systems, which obtain special 3 translational degree of freedom of the towed object only through the change of cables length. Kinematics and dynamics analysis of two parallel mechanisms are analyzed by using recursive matrix relations [9]. ZHENG Yaqing et al. [10-11] use three mobile trolley, which can move along straight line, and tow the same object, the kinematics and dynamics of the system is analyzed. Bossecher P et al. [12] analyzed dynamic stability of the system by using motion-screw slope method. Xiaobo Zhou et al. [13] discussed cable-tensions distribution problems, however, the towed object only can move on the plane. TREVISANI Alberto et al. [14] researched the workspace and cable-tensions optimization problems of system.

Through the above examples, it can be seen that 3 cables can be also achieved towing the object of 3 or 6 DOF by adding some constraints. In this paper, the three robots cooperatively tow an object of 6 DOF, which also belongs to the similar problem, but the major differences from the above mechanisms are that the end-effector of each robot is considered with 3 DOF and the cable length can change. So it makes the system more flexible, structure-reconfigurable between multiple robots. In this paper, the mathematical model of the system will be established and it will be divided into three types of systems, which are fixed cable length, variable cable length, robot-ends and cable length are changed simultaneously, to discuss some ways that how to towing the object of 6 DOF by m (m≤n) cables. According to the characteristics of the system, the following several aspects on the kinematics and dynamics of CTMRTS are discussed. In the second section, the configuration of the system is analyzed. In the third section, the coordinate systems of the system are defined, and the generalized kinematics and dynamics of the system is discussed. In the fourth section, the workspace of the system is discussed, and the optimal solution of cable tension is given. In the fifth section, the corresponding parameters of the system are given, and workspace of the three types of systems are given and analyzed by numerical calculations results with using the software MATLAB. The conclusion is also given finally. The conclusion will lay the foundation for further research about the dynamic stability and the actual control of CTMRTS.

This paper will major discuss movement of connection point between the cable and the robot-end, and not discuss the single serial robot, since the single serial robot has been developed relatively maturely.

2. System configuration

CTMRTS is parallel robots system which consisted of multiple modular serial robots, cables and towed object, which make it has an ability of collaboratively towing the same object, and let the towed object move as expected position and posture by adjusting the position of the robot-ends and the length of cables. For under-constrained systems, there is complexity of the coupling mechanics among robots, cables and towed object. The space configuration of CTMRTS is shown in figure 1.

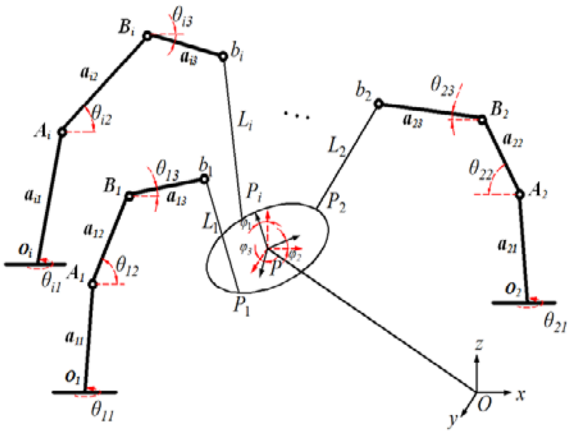


Fig. 1. The space configuration of system

The towed object is suspended under multiple robots through cables. In figure 1 the global coordinate system $\{O\}$ and the local coordinate system $\{P\}$ are established, b_i (i=1,2,⋯,m) is points of junction between cables and robot-ends, and P_i (i=1,2,⋯,m) is points of junction between cables and the towed object. A_i and B_i stands for the first and second joint of the robots respectively. a_{ij} stand for the effective length of the j^{th} root link rod on the i^{th} robot. θ_{ij} stand for joint angle of robots. $\boldsymbol{L}_i$ stand for cable position vector. $\boldsymbol{r}=(x,y,z)^T$ and $\boldsymbol{\varphi}=(\varphi_1,\varphi_2,\varphi_3)^T$, the position vector $\boldsymbol{r}$ and the posture vector $\boldsymbol{\varphi}$ of the reference point P of the towed object can describe the spatial position of the towed object in the global coordinate system {O}. The cable length can be changed by the reel of robot-end. The number m ($3 \le m < 6$) and kind of robots can be configured according to the need of actual tasks.

3. Dynamics modeling of CTMRTS

Assuming that the system is composed of m robots, and the towed object of 6 DOF, It is assumed that all cables are ideal, that is, the gravity and elastic deformation of cables are ignored. According to Fig.1, The cable length formula can be obtained by b_i, P_i.

$$L_i = \sqrt{\left(x_i - x_{pi}\right)^2 + \left(y_i - y_{pi}\right)^2 + \left(z_i - z_{pi}\right)^2} \quad i=1,2,\cdots,m \tag{1}$$

Where (x_i, y_i, z_i) is position of junction point b_i in the global coordinate system $\{O\}$, and (x_{pi}, y_{pi}, z_{pi}) is position of junction points P_i in the global coordinate system, they have following relationship.

$$\begin{bmatrix} x_{pi} \\ y_{pi} \\ z_{pi} \end{bmatrix} = \begin{bmatrix} x \\ y \\ z \end{bmatrix} + {}^{o}\boldsymbol{R}_p \begin{bmatrix} {}^{p}x_{pi} \\ {}^{p}y_{pi} \\ {}^{p}z_{pi} \end{bmatrix} \tag{2}$$

Where $\left[{}^{p}x_{pi}, {}^{p}y_{pi}, {}^{p}z_{pi}\right]^T$ is position of junction points P_i in the local coordinate system.

The absolute orientation of the towed object can be described by a general rotation matrix ${}^{o}\boldsymbol{R}_p$. The Euler representation is adopted to describe the absolute moving towed object posture, which is composed of three successive relative rotations, namely: first rotation of angle φ_3 around the Z1-axis, followed by second rotation of angle φ_2 around the rotated Y2-axis and finally followed by third rotation of angle φ_1 around the X-axis of the final moving frame P-XYZ attached to the moving towed object. With respect to the fixed global coordinate system O-xyz, the general rotation matrix can be expressed by a multiplication of three basic rotation matrices as follows:

$${}^{O}\boldsymbol{R}_P = \boldsymbol{R}_1(\mathrm{Z1}, \boldsymbol{\varphi}_3)\, \boldsymbol{R}_2(\mathrm{Y2}, \boldsymbol{\varphi}_2)\, \boldsymbol{R}_3(\mathrm{X}, \boldsymbol{\varphi}_1) \tag{3}$$

Assuming that the size of m cables tensions are T_1, T_2,⋯, T_m, then the generalized dynamic equations of the towed object based on the Newton-Euler modeling, applied with respect to mass centre P of the towed object, can be expressed in the coordinate system O-XYZ in following matrix form:

$$\boldsymbol{JT} + \boldsymbol{G} + \boldsymbol{W}_\mathrm{e} = \boldsymbol{M}\ddot{\boldsymbol{X}} \tag{4}$$

Where $\boldsymbol{W}_\mathbf{e}$ is the external force and moment exerted at the center of mass of the towed object, $\boldsymbol{J}$ is structure matrix of the towing system:

$$\boldsymbol{J} = \begin{bmatrix} J_1 & J_2 & \cdots & J_m \end{bmatrix}^\mathrm{T} \tag{5}$$

$$J_i = \begin{bmatrix} \boldsymbol{e}_i \\ ({}^{O}\boldsymbol{R}_P\, {}^{P}\boldsymbol{P}_i) \times \boldsymbol{e}_i \end{bmatrix} = \frac{1}{\left\| {}^{O}P_i - b_i \right\|} \cdot \begin{vmatrix} {}^{O}P_i - b_i \\ {}^{O}R_P \times ({}^{O}P_i - b_i) \end{vmatrix} \quad (\, i=1,2,\cdots,m) \tag{6}$$

Where $\boldsymbol{e}_i = \frac{\boldsymbol{L}_i}{\|\boldsymbol{L}_i\|}$ is defined as the unit of cable length vector. ${}^{P}\boldsymbol{P}_i$ and ${}^{O}P_i$ is the P_i's positions in the local coordinate system $\{P\}$ and the global coordinate system $\{O\}$, respectively. Cable matrix $\boldsymbol{T}$**,** gravity matrix $\boldsymbol{G}$ and mass matrix $\boldsymbol{M}$ of system can be written as following forms:

$$\boldsymbol{T} = \left[T_1, T_2, \cdots, T_m\right]^T \tag{7}$$

$$\boldsymbol{G} = \left[0,0,-M^{+}g,0,0,0\right]^T \tag{8}$$

$$\boldsymbol{M} = \begin{bmatrix} M^{+}\boldsymbol{I}_3 & 0 \\ 0 & \boldsymbol{I}' \end{bmatrix} \tag{9}$$

Where, $\boldsymbol{M}$ is the inertia matrix of system, M^{+} is the mass of the towed object, $\boldsymbol{I}_3 \in \boldsymbol{I}_{3\times3}$ is the unit matrix, $\boldsymbol{I}'$ is the inertia matrix of the towed object in the global coordinate system, it can be expressed as follow:

$$\boldsymbol{I}' = {}^{O}\boldsymbol{R}_P \cdot \boldsymbol{I} \cdot {}^{O}\boldsymbol{R}_P^{T} \tag{10}$$

Where, $\boldsymbol{I}$ is the inertia matrix of the towed object in the local coordinate system.

T_i is the cable tension, but cable can only provide one-way pull, so T_i must be positive, at the time T_i cannot exceed the maximum tension that cable can withstand to ensure system safety and stability control. The actual tension T_i satisfies the following conditions:

$$0 < T_i < T_{f\max} = \frac{T_{\lim}}{n} \tag{11}$$

Where, $T_{f\max}$ is the maximum tension that cable can withstand to ensure system safety and dynamic stability. $T_{\lim}$ is the limit tension that cable can withstand. n is safety coefficient of cable must be set up to ensure cable have a safety working status. So n is subject to $1.5 \le n \le 2$.

The acceleration of the towed object can be written as following form:

$$\ddot{\boldsymbol{X}} = [\ddot{x}, \ddot{y}, \ddot{z}, \ddot{\varphi}_1, \ddot{\varphi}_2, \ddot{\varphi}_3]^T \tag{12}$$

Where $\ddot{x}, \ddot{y}, \ddot{z}$ respectively represents the translation acceleration of the towed object in the X, Y, Z axis， $\ddot{\varphi}_1, \ddot{\varphi}_2, \ddot{\varphi}_3$ respectively represents the angular acceleration of the towed object around the X, Y, Z axis.

By Eq. (3), the cable tension can be expressed as follows:

$$\boldsymbol{T} = \boldsymbol{J}^{-1}\left(\boldsymbol{M}\ddot{\boldsymbol{X}} - \boldsymbol{G} - \boldsymbol{W}_e\right) \tag{13}$$

4. Analysis and solution of workspace of CTMRTS

The workspace of CTMRTS is characterized as the set of points where all the position that ensure every cable tension making the towed object to achieve the force balance and to satisfy the system constrains conditions. The mathematic description of the workspace of CTMRTS can be expressed as follow from:

$$\boldsymbol{W} = \left\{\left(x, y, z, \varphi_1, \varphi_2, \varphi_3\right) \in \mathbf{R}^6 \mid g_0\left(x, y, z, \varphi_1, \varphi_2, \varphi_3\right) \leqslant 0\right\} \tag{14}$$

Where $\boldsymbol{W}$ is the generalized workspace of CTMRTS, $\mathbf{R}^6$ is a six-dimensional real number domains. g_0 refers the system constrains conditions.

The Monte-Carlo algorithm based on random probability is used to calculate the workspace of the towed object. Combine Eq. (1) and Eq. (2), cables length and position of the towed object can be obtained. The position of the towed object should satisfy Eq. (15):

$$\begin{cases} \min\left(x_1, x_2, \cdots, x_{\mathrm{m}}\right) < x < \max\left(x_1, x_2, \cdots, x_{\mathrm{m}}\right) \\ \min\left(y_1, y_2, \cdots, y_{\mathrm{m}}\right) < y < \max\left(y_1, y_2, \cdots, y_{\mathrm{m}}\right) \\ \min\left(\mathrm{z}_1, \mathrm{z}_2, \cdots, \mathrm{z}_{\mathrm{m}}\right) < z < \max\left(\mathrm{z}_1, \mathrm{z}_2, \cdots, \mathrm{z}_{\mathrm{m}}\right) \end{cases} \tag{15}$$

System dynamic equations can be written in form **AT = b**. When the system will not occur the singular motion, rank(**A**)≤min(m, n). This paper studies under-constrained systems, so rank(**A**)≤m. If rank(**A**) ≠rank(**A** , **b**), the equations have not solution, that is, the position of the towed object does not satisfy the system constrains conditions; Else if rank(**A**) =rank(**A** , **b**)=m, the equation has a unique solution, that is, there is one and only one position of the towed object to satisfy the system constrains conditions; Else if rank(**A**) =rank(**A** , **b**) < m, equations have infinitely many solutions. Based on generalized inverse matrix theory, equations(13) must have the only least squares solutions:

$$\boldsymbol{T}' = \boldsymbol{J}^{+}(\boldsymbol{M}\ddot{\boldsymbol{X}} - \boldsymbol{G} - \boldsymbol{W}_{\mathrm{e}}) \tag{16}$$

Where $\boldsymbol{J}^{+} = \boldsymbol{J}^{\mathrm{T}}\left(\boldsymbol{J}\times\boldsymbol{J}^{\mathrm{T}}\right)^{-1}$ is Moore-Penrose inverse of structure matrix $\boldsymbol{J}$, minimal norm least square solution is a set of special solution for Eq. (3), its general solution can be expressed as follows form:

$$\boldsymbol{T}^{*} = \boldsymbol{T}' + Null(\boldsymbol{J}) \cdot \lambda \tag{17}$$

Where $Null(\boldsymbol{J})$ is to the null space vector of $\boldsymbol{J}$, $\lambda\left(\lambda \in (0,1)\right)$ is any scalar. At this time, physical significance of $\boldsymbol{T}^{*}$ is optimal solution of cables tension.

The major analysis methods of workspace have analytical and numerical methods. However, analytical method could not completely describe the workspace for complicated systems, so numerical method is used to analyze workspace of the towing system. The calculation steps are as follows:

(a) First of all, based on geometry space constraints of the system an initial position space scope of robot is given.

(b) Then using the Monte-Carlo algorithm based on random probability the position data of robot-ends and the posture data of towed object are given one by one.

(c) The cable length and position of the towed object can be obtained using the Eq. (1) and Eq.(2). And verifying the position whether satisfied the constraints condition Eq. (15), if it is and goes to (d), if it is not and returns to (b).

(d) It is judge whether the system matrix meets rank(**A**) =rank(**A**, **b**), if it is and goes to (e), if it is not and returns to (b).

(e) If rank(**A**) =rank(**A**, **b**) =m, the cables tension **T** can be obtained using the Eq. (13); Else if rank(**A**) =rank(**A**, **b**) <m, the cables tension **T** can be obtained using the Eq. (18).

(f) It is judge whether all elements of **T** meets Eq. (12), if it is and records the position of the towed; if it is not and returns to (b).

(g) Repeat steps (b) - (f) until end.

Some important variable symbols are defined in Table 1.

Table 1

Various symbols being used

P_i	The connection point between the i^{th} cable and the towed object
P	Mass centre P' of the towed object
^OR_P	Rotation matrix of the towed object
L_i	Length of the i^{th} cable
T_i	Tension of the i^{th} cable
$\boldsymbol{r}$	The position vector of the towed object in the global coordinate system
$\boldsymbol{\varphi}$	The posture vector of the towed object in the global coordinate system
$\boldsymbol{J}$	Structure matrix of the towing system
$\boldsymbol{J}^+$	Moore-Penrose inverse of structure matrix $\boldsymbol{J}$
$\boldsymbol{W}_\mathbf{e}$	The external force and moment exerted at the mass centre of the towed object
$\boldsymbol{W}$	The generalized workspace of CTMRTS
b_i	Coordinate of connection point b_i in local coordinate system
$\ddot{\boldsymbol{X}}$	Acceleration of the towed object in the global coordinate system
I	Inertia matrix of the towed object in the local coordinate system
I'	Inertia matrix of the towed object in the global coordinate system
T_i	Tension of the i^{th} cable
$\boldsymbol{M}$	the inertia matrix of system
M^+	Mass of the towed object
$\boldsymbol{G}$	Gravity matrix of the towed object

5. Simulation and analysis

In this paper, three robots are deployed to tow the same towed object of 6 DOF as an example. Projection of robot-ends' workspace onto the XOY plane is shown in Figure 2. Three robots can reach position range in the Z direction is (1m, 1.4m), three connection points P_1, P_2 and P_3 form an equilateral triangle, and sides long is l = 0.1m. The mass of the towed object M= 10kg, the inertia of the towed object are I_x=0.54，I_y=0.26，I_z=0.28 respectively, the posture $\varphi_1,\varphi_2,\varphi_3$ range of towed object are (-1rad, 1rad), the maximum tension of cable T_{fmax}=500N. From which has been discussed above, we know that the object's position should be in the triangular prism that consisted of points b_i and projection points of points b_i on the XOY plane. Calculating loop of 60000 times, Workspace of three types of systems are simulated by numerical method.

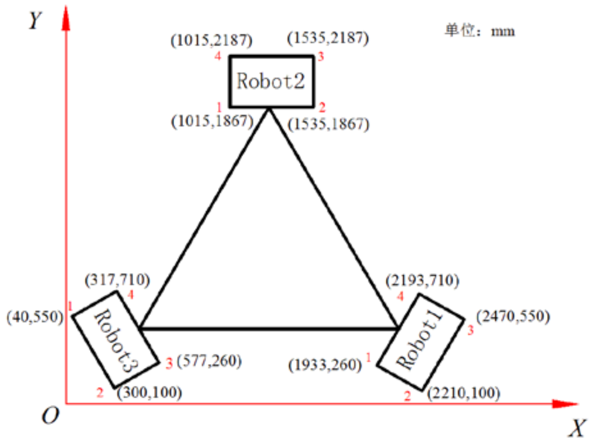


Fig. 2. Projection of robot-ends workspace onto the XOY plane

5.1 Fixed cable length

Fixed cable length refers to realize position and posture of the towed object only through changing the positions of robot-ends. We assume that cables length are fixed, and L_i=1.2m. In this case, the simulation results of the reachable 3D workspace for the CTMRTS and the projections of workspace onto the XOY plane, XOZ plane and YOZ plane are shown in Figure 3.

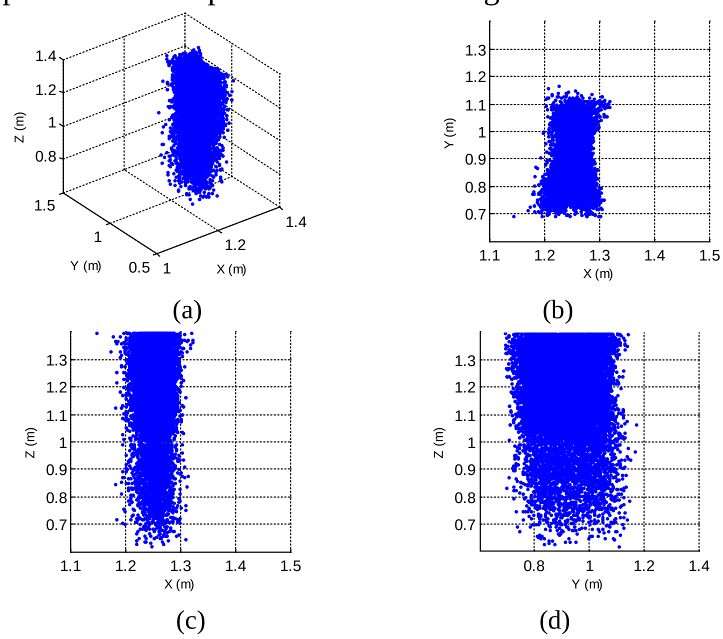
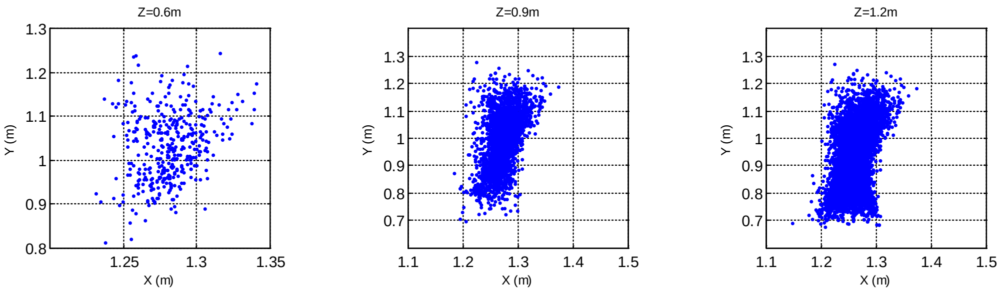


Fig. 3. Workspace for the CTMRTS (a) and the projections of workspace onto the XOY plane (b), XOZ plane (c) and YOZ plane (d)

Referring to Fig. 3, the lower half of the workspace is approximately an upside-down cone, the upper half of the workspace is approximately a rectangular prism. The range of values for X is (1.15，1.34)，the range of values for Y is (0.7，1.18)，the range of values for Z is (0.6，1.38).

To more clearly show that their working situations and performance at different height, the cross section of Z=0.6m, Z=0.9m and Z=1.2m are given in Figure 4. Figure 4(a) shows that the cross section of Z=0.6m is approximately triangle, figure 4(c) shows that the cross section of Z=1.2m is approximately rectangle, Figure 4(b) and Figure 4(c) show that the higher of the workspace, the cross section is closer rectangle, the main reasons have two aspects: (1) cables length are fixed. (2) workspaces of all robot-end are rectangular prisms.

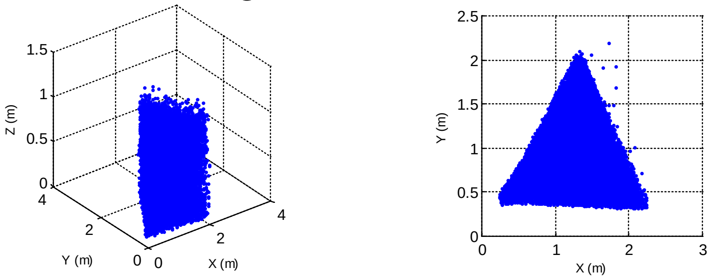


(a) (b) (c)

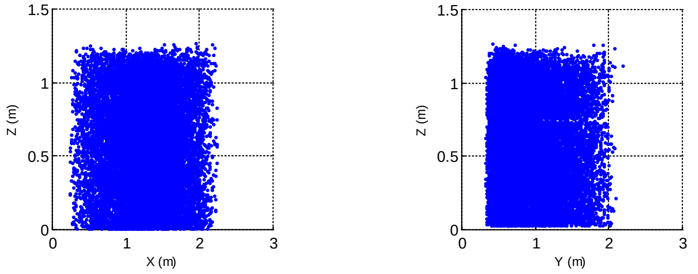
Fig. 4. The cross section of Z=0.6m (a), Z=0.9m (b) and Z=1.2m (c)

5.2 Variable cable length

Variable cable length refers to realize position and posture of the towed object only through changing cables length, however, the robot-ends are fixed. In this paper, the robot-end is fixed in the centre of itself workspace, respectively, so robot-ends' position are b_1(2.2, 0.45, 1.2)，b_2(1.275, 2.027, 1.2)，b_3(0.308, 0.405, 1.2). In this case, the simulation results of the reachable 3D workspace for the CTMRTS and the projections of workspace onto the XOY plane, XOZ plane and YOZ plane are shown in Figure 5.



(a) (b)



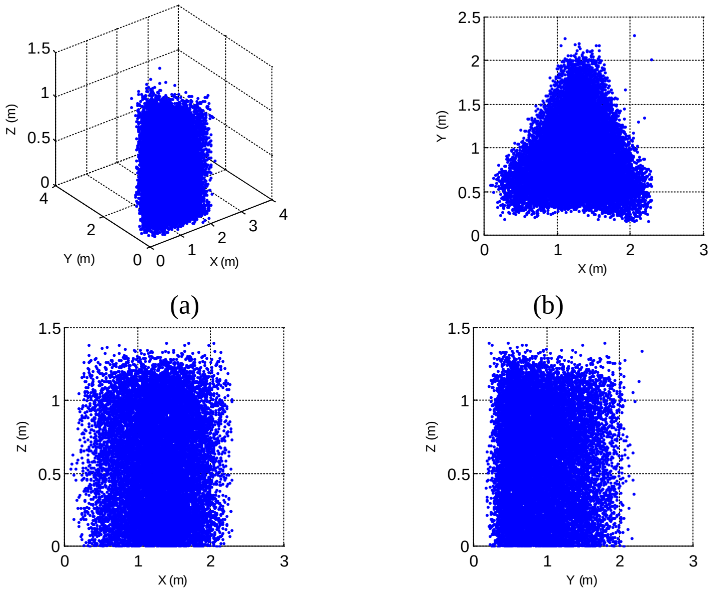
(c) (d)

Fig. 5. Workspace for the CTMRTS (a) and the projections of workspace onto the XOY plane (b), XOZ plane (c) and YOZ plane (d)

Referring to Fig. 5, at the case of variable cable length, the object's position should be in the triangular prism that consisted of points b_i and projection points of points b_i on the XOY plane. The range of values for X is (0.31，2.2)，the range of values for Y is (0.45，2)，the range of values for Z is (0，1.18).

5.3 Robot-ends and cables length are change simultaneously

Robot-ends and cables length are change simultaneously refers to realize position and posture of the towed object through simultaneously changing robot-ends' position and cables length. In this case, the simulation results of the reachable 3D workspace for the CTMRTS and the projections of workspace onto the XOY plane, XOZ plane and YOZ plane are shown in Figure 6.



(a) (b)

(c) (d)

Fig. 6. Workspace for the CTMRTS (a) and the projections of workspace onto the XOY plane (b), XOZ plane (c) and YOZ plane (d)

Referring to Fig. 6, at the case of robot-ends and cables length are change simultaneously, the object's position should be in the triangular prism that consisted of points b_i and projection points of points b_i on the XOY plane. The range of values for X is (0.15，2.3), the range of values for Y is (0.2，2.2), the range of values for Z is (0，1.38).

It would be shown that the analysis and simulation of the robots system are performed for three cases: fixed cable length, variable cable length and the third case, when robot-ends and cables length are changed simultaneously. So, the workspace volume is changing from small to large successively. And they have content relationships, successively.

6. Conclusion

In this paper, CTMRTS was divided into three types of systems by different driving configurations, some questions of CTMRTS were discussed for under-constrained systems which can realize 6 DOF of the towed object by using m cables. The generalized dynamic model of CTMRTS was established by using Newton - Euler method. The workspace of CTMRTS was analyzed, optimal solution of the cables tension was given. Finally, the parameters of the practical system, which can realize 6 DOF of the towed object by using 3 cables, were given, the three types of systems' workspaces were calculated by using the Monte-Carlo algorithm, and the corresponding workspace of the three types of systems of CTMRTS were obtained. The volume size and content relationships of the three types of systems were given. Furthermore, this research can potentially be extended to address other important issues, such as cooperatively control of CTMRTS, stiffness and dynamical stability analysis of CTMRTS.

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R E F E R E N C E S

[1]. *Wei LI, Zhigang Zhao, Guang Tian Shi，et a*l. "Inverse Dynamics Analysis And Simulation of a Class of Under- Constrained Cable-Driven Parallel System". UPB Scientific Bulletin, Series D: Mechanical Engineering, **vol. 78**, no. 1, 2016, pp. 87-98.

[2]. *Zhao Zhigang, Lu Tian-Sheng.* "Dynamics Analysis of Close-coupling Multiple Helicopters System." Chinese Journal of Aeronautics. **Vol.** 21, no. 1, 2008, pp. 71-78.

[3]. *Agheli, M.;Nestinger, S.S.* “Comprehensive closed-form solution for the reachable workspace of 2-RPR planar parallel mechanisms”. Mechanism and Machine Theory, **vol. 74**, no. 4, 2014, pp. 102-116.

[4]. *Ming A，Higuchi T.* “Study on multiple degree of freedom positioning mechanisms using wires (Part 1) : Concept，design and control”. International Journal of the Japan Society for Precision Engineering, **vol.** 28, no. 2, 1994, pp. 131-138.

[5]. *Bin Zi, Sen Qian, Huafeng Ding, et al*. “Design and Analysis of Cooperative Cable Parallel Manipulators for Multiple Mobile Cranes”, International Journal of Advanced Robotic Systems”, **vol. 9**, no. 1, 2012, pp. 1−10.

[6]. *Bin Zi, Zhen-Cai Zhu, Jing-Li Du.* Analysis and control of the cable-supporting system including actuator dynamics”. Control Engineering Practice. 2011, **vol.19**, no. 5, pp. 491-501

[7]. *Bin Zi, Jun Lin, Sen Qian.* “Localization, obstacle avoidance planning and control of a cooperative cable parallel robot for multiple mobile cranes”, Robotics and Computer-Integrated Manufacturing. **vol.** 34, no. 9, 2015, pp. 105-123.

[8]. *Bin Zi, Huafeng Ding, Xia Wu, et al*. “Error modeling and sensitivity analysis of a hybrid-driven based cable parallel manipulator”, Precision Engineering”, **vol.** 38, no. 1, 2014, pp. 197-211.

[9]. *Stefan Staicu*, “Matrix modeling of inverse dynamics of spatial and planar parallel robots”, Multibody System Dynamics, **vol.** 27, no. 2, 2012, pp. 239-265.

[10].*Yaqing Zheng, Qi Lin，Jian-Po Wu, et al*. Analysis of Inverse Kinematics and Dynamics of a Novel 6-Degree-of–freedom Wire-Driven Parallel Gantry Crane Robot. IEEE/ASME International Conference on Advanced Intelligent Mechatronics, Singapore, 2009.

[11]. *Lan Yu, Yaqing Zheng.* Configuration Design And Analysis of Generalized Inverse Pose Kinematic Problem of 6-DOF Wire-Driven Gantry Crane Robots. International Conference on Automatic Control and Artificial Intelligence, Xiamen, CHINA, 2012.

[12]. *Bosscher P, Ebert I.* A stability measure for underconstrained cable-driven robots. In: Proceedings of 2004 IEEE International Conference on Robotics＆Automation, New Orleans, LA, 2004.

[13]. *Xiaobo Zhou, Seung-kook Jun, Venkat Krovi.* “Tension distribution shaping via reconfigurable attachment in planar mobile cable robots”, Robotica, **vol.** 32, no. 10, 2014, pp. 245-256.

[14]. *Trevisani Alberto.* “Planning of DynamiCally Feasible Trajectories for Translational, Planar, and Undercon- Strained Cable-Driven Robots”, Journal of Systems Science & Complexity, **vol.** 26, no. 10, 2013, pp. 695-717.