Article ID: 1000-8152(2001)03-0328-05

A New Type of Flexible Parallel Link Manipulator Actuated by Cable

WANG Wenli and DUAN Baoyan
(Research Institute of Mechatronics, School of Mechanical and Electronic Engineering, Xi'an University of Electronic Technology · Xi'an, 710071, P.R.China)
PENG Bo and NAN Rendong
(Beijing Astronomy Observatory, China Academy of Science · Beijing, 100012, P.R.China)

Abstract: The design project of the feedback source supporting system for five-hundred meter aperture spherical radio telescope (FAST) is introduced. This project is a new type model of this flexible manipulator system. A 5-meter prototype has been designed and constructed, the experimental results show that the new type of flexible parallel manipulator is feasible in principle and effective in use.

Key words: parallel manipulator; flexible cable; large radio telescope; stewart platform
Document code: A

悬索驱动的新型柔性并联机器人

王文利　段宝岩　彭　勃　南仁东
(西安电子科技大学机电工程学院机电研究所·西安,710071)　(北京天文观测中心,中国科学院北京天文台·北京,100012)

摘要:介绍了500米口径球面射电望远镜FAST馈源支撑结构创新设计方案,该方案采用六根悬索和馈源舱构成的新型柔性并联机器人系统.建立了柔性机器人系统的逆运动学模型,设计并制造了该系统的5米模型,实验结果表明这种新型柔性并联系统在原理上是可行的.

关键词:并联机器人;柔索;大射电望远镜;stewart平台

1 Introduction

FAST (five-hunderd meter aperture spherical telescope) is an advance engineering of the international large radio telescope plan. It will be built at a karst area in Guizhou province of China. The scope of bandwidth covers from meter wave, decimeter wave to centimeter wave (0.3 ~ 8.8GHz)[1,2].

So far, the largest spherical radio telescope in the world is Arecibo reflector with 305-meter-diameter built in 1970's and located in Puerto Rico, USA. Due to the technique limitation of that time, the feed control and tracking system was implemented with mechanical means. The weight of the feed structure suspended by several long cables is over 800 tons. There exist three shortages of Arecibo telescope: low positioning accuracy, single wave-band observation and expensive cost[3].

Considering the mechanical, electronic, optic and control technologies together, a completely different design scheme from Arecibo style could be proposed as shown in Fig. 1. In this project, the 800-ton-weight Arecibo feed system is thrown away and replaced by a cabin of only about 20 tons and feeds are laid in the cabin. The cabin is suspended with six cables from six concrete towers on the hill. The six cables are driven by six sets of servomechanism so that the scanning movement of feed along design trajectory can be realized.

Considering the observation frequency up to 8.8GHz, the difference of the feed's real position from theoretical position under external load, for instance, wind, can not be over 4mm. It is difficult to achieve such high accuracy with only cables. For the sake of this, a new type of macro-micro adjustment system is proposed in this article. The cabin actuated by six cables is called the macro part. The micro part, which is mounted in the cabin, is a Stewart platform. Nine feeds are fixed on the movable platform of Stewart platform.

* Foundation item: supported by the National Natural Science Foundation of China (59675040) and the Key Project of Knowledge Innovation Engineering of the Chinese Academy of Sciences (Pre-study of Large Radio Telescope FAST).
Received date: 2000-03-27; Revised date: 2001-01-15.

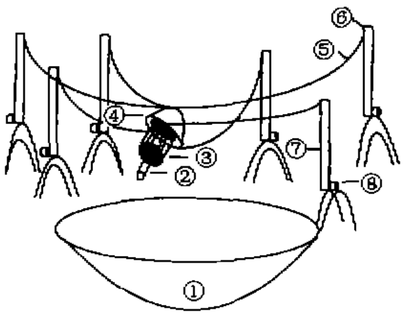


Fig. 1 The systhetic design of FAST

During operation, the desired position and orientation of the cabin and feed will be affected by the random loads for example, wind. In order to know the real position and orientation of canbin and feed in time, a set of laser automatic positioning system is employed, which gives the real-time positions and orientations of cabin and feeds. In this case, a high tracking accuracy of the feed can be obtained. In addition, the high performance-cost ratio can also be realized, for only one tenth of Arecibo feed system's cost is required to make this new feed system.

2 The trajectory of feed

Considering the geographical position (North latitude 25 degree, East longitude 65degree) of Guizhou karst area of China, the fixed coordinate system $OXYZ$ is estabilished (shown in Fig. 2). The coordinate system $OXYZ$ is given where O is at the lowest point of the main spherical reflector, Z-coordinate pointing at zenith, X-coordinate toward north and Y-coordinate toward west. For satisfying the need of astronomic observation, the trajectory of feed is deduced with respect to the system $OXYZ$ (as shown in Fig.2)[3]:

$$\begin{cases} x = \frac{R}{2}(\cos\delta\cos H\cos 65^\circ - \sin\delta\sin 65^\circ), \\ y = -\frac{R}{2}\cos\delta\sin H, \\ z = -\frac{R}{2}(\cos\delta\cos H\sin 65^\circ + \sin\delta\cos 65^\circ) + R. \end{cases} \tag{1}$$

In which, R is the radius of spherical reflector; δ is the declination of star being observed, H is the hour-angle.

Since the limit of zenith angle of antenna, the view scope is constrained within $(-15^\circ, 65^\circ)$. Consequently the useful scale of hour angle H, for the given declination δ, is determined by

$$|H| < |\arccos[(0.845 - 0.466\sin\delta)/\cos\delta]|. \tag{2}$$

If $\delta = 30^\circ$ is concerned, the scale of hour angle becomes $(-45^\circ, 45^\circ)$. Whthin this scale, three typical positions with 0°, −45° and 45°are considered as D_1, D_2 and D_3 respectively (shown is Fig.2). The coordinates of the above three typical points are

$D_1(-1355.9,\ 0.0,\ 15616.2)$(cm),

$D_2(-3023.61,\ 9526.82,\ 19192.86)$(cm),

$D_3(-3023.61,\ -9526.82,\ 19192.86)$ (cm)

respectively. Six fixed points are

$A(0.0,\ -25000.0,\ 25000.0)$(cm),

$B(21650.64,\ 12500.0,\ 25000.0)$(cm),

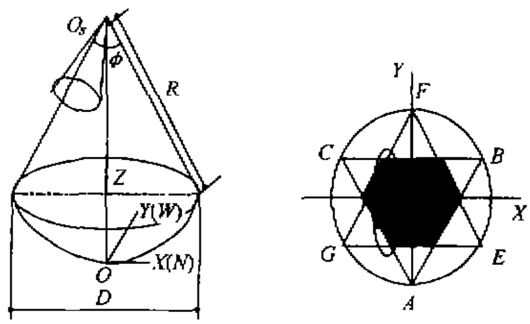
$C(-21650.64,\ 12500.0,\ 25000.0)$(cm),

$E(21650.6,\ -12500.0,\ 25000.0)$(cm),

$F(0.0,\ 25000.0,\ 25000.0)$(cm),

$G(-21650.6,\ -12500.0,\ 25000.0)$ (cm)

respectively. The real trajectory is the continuous curve D_2D_3 and the darksome area is the accessible workspace of cabin (shown in Fig.2(b)).



(a) The trajectory of feed (b) The planform of the trajectory

Fig. 2 The trajectory of feed with respect to the fixed coordinate system

3 Deduction of the cable's function and cable's tension

For a cable shown in Fig. 3, the function can be mathematically deduced as[3],

$$y(x) = -k\,\mathrm{ch}\left(\frac{x}{k} + C_2\right) + C_1, \tag{3}$$

where $k = \frac{\widetilde{H}}{q}$, $\widetilde{H}$ is the horizontal tension of cable at x; q is the weight of unit length of cable. In formula (4), two unknown constants C_1 and C_2 can be found from

$$\begin{cases} C_1 - k\mathrm{ch}(C_2) = 0, \\ C_1 - k\mathrm{ch}(\frac{1}{k} + C_2) = h, \end{cases} \tag{4}$$

Obviously, it is hyperbolic equation, which needs to be solved by numerical method.

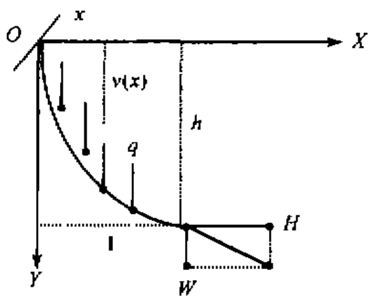


Fig. 3 A suspended cable of FAST

4 Inverse kinematics model of cable system

The basic idea of Stewart platform parallel link manipulator is used in the synthetic design of FAST. The difference between FAST and Stewart platform is to use cables as the parallel links and to use winches as the actuators. Viewing from this point, six-cable structure in FAST system can be considered as a set of flexible parallel manipulator with 6-DOF similar to Stewart platform. So the adjustment system of FAST is to be understood as a macro-micro manipulator system.

Based on the parallel manipulator theory, the so-called inverse kinematics solution is to calculate the inputs from the known location and orientation of output. The cabin is the output and six cables are inputs in FAST. The inverse solution of the cabin is necessary to implement computer-controlled motion of the cabin. We have gained the tracking trajectory of feed from karst geographical position of Guizhou province of China in the Section 2 of this paper. For the sake of simplicity, we assume that the feed is located at the center of cabin and the barycenter of cabin system lies at the middle axis $O_1 O_2$. From the electrical target requirement of feed, the middle axis $O_1 O_2$ must be overlapped with radius of the main reflector. The carrier-based coordinate system $O_2X'Y'Z'$ is estabilished on the cabin. The coordinate plane $X'O_2Y'$ lies in the bottom of cabin, Z' axis point to O_1. Thus, the center of cabin O_2 is located at the tracking point and the orientation of cabin is determined except for the rotational freedom with respect to Z' axis (shown in Fig.4). The fixed coordinate system $OXYZ$ is as the same as shown in Fig.2.

So the position of the movable cabin can be expressed by $O_2(x_{O_2}, y_{O_2}, z_{O_2})$ with respect to the coordinate system $OXYZ$ and the rotation matrix T. Now let us consider how to determine the rotational freedom with respect to Z' axis.

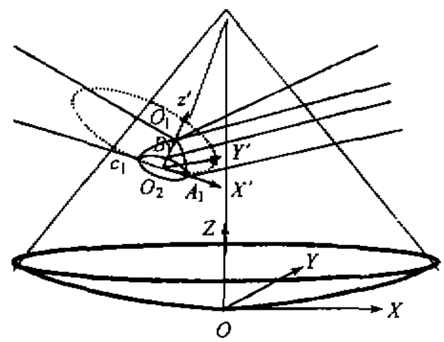


Fig. 4 The carrier-based coordinate system and the fixed coordinate system

Three cables connect at the top O_1 and the other three cables connect at points A_1, B_1 and C_1 respectively (shown in Fig.4). Because the cable must be in tension and can not be slack, we utilize the iterative method to search the rotational angle with respect to Z' axis. If the rotational angle with respect to Z' is given, coordinates of points A_1, B_1 and C with respect to $OXYZ$ can be obtained. Considering the static equilibrium about the cabin gives

$$\begin{aligned} &\sum F_x = 0, \sum F_y = 0, \sum F_z = 0, \\ &\sum M_x = 0, \sum M_y = 0, \sum M_z = 0. \end{aligned} \tag{5}$$

Because the cable's tension and cable's length are in coupling, to solve equation (5), the length must be solved from the suspended equation (3). There exist twelve integral constants in six cables. These constants can be expressed with the boundary conditions of $A, B, C, E, F, G, O_1, A_1, B_1, C_1$.

From the trajectroy equation (1) and the rotational angle with respect to Z', coordinates of points O_1, O_2, A_1, B_1 and C_1 with respect to the fixed coordinate system $OXYZ$ can be obtained as follows,

$$\begin{bmatrix} x_i \\ y_i \\ z_i \end{bmatrix} = T \begin{bmatrix} x_i' \\ y_i' \\ z_i' \end{bmatrix} + \begin{bmatrix} x_{o_2} \\ y_{o_2} \\ z_{o_2} \end{bmatrix}. \tag{6}$$

where x_i, y_i and z_i are the coordinates of one point of cabin with respect to $OXYZ$. x_i', y_i' and z_i' are the coordinates of the same point with respect to the system $O_2X'Y'Z'$. x_{O_2}, y_{O_2} and z_{O_2} are the coordinates of point O_2 with respect to the system $OXYZ$. T is the rotation matrix. The coordinate system $O_2X'Y'Z'$ is gained from the coordinate system $OXYZ$ as follows:

Step 1 Move the coordinate system $OXYZ$ parallel to the point O_2;

Step 2 Rotate at an angle Ψ with respect to X axis, let the new Y axis vertical to $O_1 O_2$;

Step 3 Rotate at an angle θ with respect to the new Y axis (Y''), let the new X axis vertical to $O_1 O_2$;

Step 4 Thus the new Z axis (Z') points to O_1, O_2; then rotate at an angle ϕ with respect to Z' axis, gained the system $O_1X'Y'Z'$.

Based on the above rotation process, the matrix T is:

$$T = T_X(\Psi)T_{Y''}(\theta)T_{Z'}(\phi) = \begin{bmatrix} C\theta C\phi & -C\theta S\phi & S\theta \\ S\Psi S\theta C\phi + C\Psi S\phi & C\Psi C\phi - S\Psi S\theta S\phi & -S\Psi C\theta \\ S\Psi S\phi - C\Psi S\theta C\phi & C\Psi S\theta S\phi + S\Psi C\phi & C\Psi C\theta \end{bmatrix} \quad (7)$$

where the symbols S and C stand for cosine and sine of an angle. Ψ and θ are determined by coordinates of points $O_1(x_{O_1}, y_{O_1}, z_{O_1})$ and $O_2(x_{O_2}, y_{O_2}, z_{O_2})$ in the following form:

$$\Psi = \operatorname{arcctg}\left(\frac{\sqrt{(y_{O_1} - y_{O_2})^2 + (z_{O_1} - z_{O_2})^2}}{x_{O_1} - x_{O_2}}\right), \quad (8)$$

$$\theta = \operatorname{arcctg}\left(\frac{\sqrt{(x_{O_1} - x_{O_2})^2 + (z_{O_1} - z_{O_2})^2}}{y_{O_1} - y_{O_2}}\right). \quad (9)$$

If the rotational angle ϕ with respect to Z' were given, the rotation matrix T is known. Thus one can compute x_i, y_i and z_i. The angle ϕ will be determined by the iterative method as follows:

Step 1 Given a rotational angle ϕ, the rotational matrix T and coordinates of A_1, B_1 and C_1 with respect to the system $O_2X'Y'Z'$ could be obtained.

Step 2 Substitute them into formula (6), one can obtain the coordinates of these points with respect to the system $OXYZ$.

Step 3 Uniting formula (5) ~ (7), one can solve a set of tensions. If every tension is positive, the cabin is in static equilibrium and stop. Otherwise let $\phi = \phi + d\phi$, solve (5) ~ (7) again until searching a set of positive tensions.

Thus the position and orientation of cabin and the tensions of six cables at one trajectory point in static equilibrium has been searched.

By the above method, the lengths and the tensions of six cables are shown in Table 1 and Table 2 when the center of cabin is located at typical points D_1, D_2, D_3.

Table 1 Length of cable at D_1, D_2 and D_3

Point	Length of cable/cm					
	S_A	S_B	S_C	S_E	S_F	S_G
D_1	26567.9	27743.7	25394.4	27701.3	26640.2	25535.2
D_2	35998.6	25252.9	19443.9	33398.9	16885.9	29316.9
D_3	16513.4	34300.5	29205.8	25455.4	34929.5	19758.6

Table 2 Tension of cable end point at D_1, D_2 and D_3

Point	Tension of cable end point/kg					
	F_A	F_B	F_C	F_E	F_F	F_G
D_1	4587.6	3633.2	5548.8	17943.9	18033.8	18129.2
D_2	2514.6	21655.6	30962.6	17141.7	14669.3	10304.4
D_3	31393.3	2481.1	10236.6	11382.7	25343.8	14964.2

On the basis of the required error of cabin, the trajectory can be divided into many discrete points. Utilizing the above iterative method one can get the length and tension of every cable respectively corresponding to every discrete point. The location and orientation of cabin are controlled through pulling or releasing six cables by servomechanisms.

5 Experiment on the flexible parallel manipulator actuated by cable

In order to verify the design idea and the key technologies of the new type of flexible parallel manipulator, a 5-meter experimental model has been designed and constructed. The framework of the model is a six-legged structure resting on six support points. The legs are 2.5-meter high. The cabin is selected as a spherical object, which is 40cm in diameter and 20cm in height. The cabin's weight is 6kg. The suspended cable is a steel wire that is 1.2mm in diameter. Considering this system is a low speed follow-up system, six DC torque motors are selected as servomotors. The pulse width modulation (PWM) method is used to control the velocity of the servomotor. In order to obtain the accurate control of the lengths of the cables, six angle encoders are located on the winches. The general frame of the 5-meter model is shown in Fig.5.

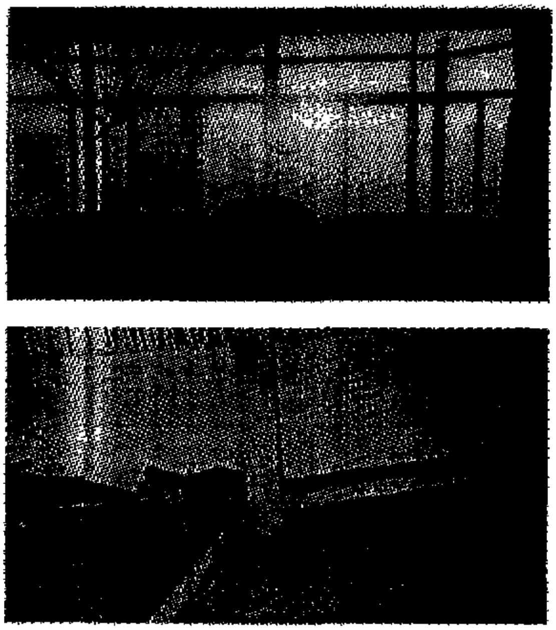


Fig.5 The framework of the 5-meter experimental prototype

Considering that the flexible parallel manipulator is a distributed system, the control system is designed as a distributed control architecture including a PC computer as the host computer and six microcomputers as the servo control computers. The host computer accomplishes the system management, the computation of the scan trajectory, the kinematics planning of the cable and cabin system, and so on. The microcomputers are double closed-loop servo systems with position and velocity control, which control the velocity and the position of the winch given by the host computer.

In terms of the requirement of the astronomical observation, the feed support system works under two kinds of modes: searching radio source and tracking radio source. When the system is searching the radio source, the chief task is quickly to position the cabin (about 50cm/s), but the positioning accuracy is not required. But the positioning accuracy will be the first-line requirement when the system is tracking the radio source. Under this condition, the velocity of the cabin ranges from 1cm/s to 2cm/s. Based on the distinct requirements of the two work modes, the double control strategy of Fuzzy and Fuzzy-PID is employed in the flexible parallel manipulator. The Fuzzy control method is used in searching radio source and the Fuzzy-PID control method is used in tracking radio source.

In the experiments, some trajectories are followed by the cabin. The measurement results indicate that the position error of the cabin center is less than 1cm and the orientation error of the cabin less than 0.5 degree. At the same time the cabin is in a stable condition when the cabin is positioned at the extreme position and orientation. There exist two reasons why the position precision can not be improved. A reason is that the control system is not a full closed-loop system including the cabin, in other words, the real-time measurement signal of the position and the orientation of the cabin is not feedback to the host computer. Another reason is the low demarcation precision of the total system. The future experiment will improve the position precision of the cabin by using more accurate devices and making a full closed-loop control system including the cabin.

6 Conclusion

This paper introduces a new type of flexible parallel link manipulator employed in the design project of large spherical radio telescope (FAST). The cabin actuated by six cables can be regarded as a flexible parallel mechanism similar to Stewart platform. The inverse kinematics model of cabin has been deduced. A 5m prototype has been designed and constructed, the results show that this new type of flexible parallel manipulator is feasible in principle and effective in use.

References

[1] Li Hui. China hopes to move FAST on largest telescope [J]. Science of America, 1998, 281(7):771

[2] Nan R D, Qiu Y H, Peng B, et al. Report of 1999-Annual Academic Conference of Five-Hundred-Meter Aperture Spherical Telescope [R]. Beijing, China, 1999, 7–10

[3] Duan B Y. A new design project of the line feed structure for large spherical radio telescope and its nonlinear dynamic analysis [J]. Int. J. Mechatronics, 1999, 9(1):53–64

本文作者简介

王文利 1971年生.西安电子科技大学机电工程学院博士研究生.主要从事机电一体化研究.已发表论文20多篇.

段宝岩 1955年生.西安电子科技大学教授,博士生导师,副校长.主要研究方向:机电一体化,面向工程的广义优化设计.

彭 勃 1966年生.北京天文台研究员.博士.从事射电天文学研究.

南仁东 1941年生.北京天文台研究员,博士,博士生导师.主要从事射电天文学及其仪器的研究.