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Spatial Six-Degree of Freedom Cable Robot Workspace Design and Movement Analysis of the Moving Platform

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ABSTRACT

This paper investigated spatial six degree of freedom cable robot workspace design and analysis for the movement of the moving platform.Therefore, the kinematic model is discussed after the introduction of spatial cable robot. Then, the cable powers are calculated and robot workspace is defined using the applied modeling.Then, thekinematic Global Condition Index (GCI) is presented to measure the quality of robot function on the entire workspace. Then, MATLAB software is used to stimulate workspace volume and kinematic parameters for different ratios of the Moving Platform to the fixed one, different geometrical configurations and various orientations of the moving plate based on underlying modeling and workspace analysis. Analysis done for this type of robots can be useful under different surface conditions.
Key words:*Cable robot, workspace, kinematic modeling, kinematic parameter, Moving Platform, geometric configuration*

INTRODUCTION

In recent years the use of robots has increased for high accuracy and reliability, speed, non-vulnerability in contaminated environments and the ability to carry heavy loads and found special place in the military, industrial and medical sectors. Robots are divided into two types of serial manipulator and parallel manipulator on the basis of kinematics chain. There are two fixed and moving platforms in the structure of parallel robots that are connected by several kinematics chains ofserial type. The robots, despite having a small work space, are able to produce movements of high accuracy. Traditional parallel robots are led by sliding stimuli. Some conventional sliding operators contain hydraulic, pneumatic and engine pistons driven by screws. These systems are large, heavy and cumbersome. To solve the problem of limited workspace in the new generation of parallel robots it is proposed that steel cables stimulated by electric motors are used rather than cylinder- pistons hydraulic operators. With this change in the structure of the parallel robot, the final element of the robot can be controlled by stimulus cables from far distances.Therobot used in this paper is a parallel robot with spatial mechanisms and kinematics chain made of steel cables inhibited by two fixed and moving platforms.

In a cable suspended robot, moving platform is suspending and the robot performance is by cables that are connected to the base. Cable robots have several advantages over conventional serial or parallel robots. They have high load to weight ratio and much larger workspace mainly limited to the cable length. They are suitable for applications of high speed [1] lifting heavy loads, filming in sports stadiums [2] and many others. Extensive studies have been done on serial and parallel robots, while only a few of these studies have been conducted on cable robots. Cable robots are used effectively in lighter and larger plans and to achieve longer workspace such as shipbuilding and hangars.However, the requirements of a cablein a robot cable are tougher than the legs activated with linear stimuli in a conventional parallel robot. Cables can only tolerate the ship load. Therefore, modeling of the workspace and the analysis of the design of robot cable is different from that of the parallel robot.

Cable robots havea short but growing history. One of the systems taking advantage of the cable in design was Robocrane developed at NIST (The NIST Robocrane) [3]. In 1999, Maeda et al. [4] introduced WARP six-degree of freedom robot. The robots designed with an emphasis on optimizing the workspace can be used in quickly assembling of light parts. Cable robots are widely used for transporting and unloading cargo in the shipping industry. In 2004, So-Ryoek[5] examined a two-stage cable robot, a robot with two moving platforms serially connected. Sea conditions introduced as disturbance system and disturbance is applied during modeling of the two-stage robot. A robust controller is designed to track the desired path of work-spot in the presence of disturbance. Other studies include extremely high-speed robot [1], tendon Stewart moving platform [6], parallel wire mechanism to measure the position and pose of the robot [7], the design of controllers for cable robot [8].

For the design and the analysis of the workspace, the optimal design of the robot will be examined and the optimal design of the robot commonly refers to the largest workspace, minimum singular valies, large output power, and high accuracy and so on. This paper tries to discuss aspects of optimal design of six-degree of freedom cable robot given the changes in the workspace volume and the robot accuracy using different geometric configurations, different sizes and orientations of moving platforms. To measure different aspects concerning the optimal design, a measure called performance index is used. By definition, performance index is a term used when referring to methods comparing the quality design of a parallel robot to another. A common performance index is the condition number of Jacobian matrix used to measure the control accuracy of the robot.

This article is organized as follows: Section 2 describes the kinematic modeling of six-degree of freedom cable robot. Section 3 obtains the cable forces using the modeling and defines the workspace. Section 4 deals with the general condition index (GCI). In Section 5, based on fundamental modeling and workspace analysis, workspace volume and GCI are simulated for various geometric configurations, different proportions of fixed and moving platforms and different directions of moving platform.

Kinematic modeling

The model used has six cables and six degrees of freedom. The robot has two fixed and moving platforms and six cables; each cable is connected on one side to the junction of the fixed platform$O_{b_i}$and on the other side to the junction of the moving platform E_{a_i}shown in Figure 1 in the form of a six-degree of freedom system. O is the origin of the fixed frame$x_0 y_0 z_0$coincided on the centerof the mass of the base platform (BP) and O_E is the origin of the moving frame$x_E y_E z_E$coincided onthe center of the mass of themoving platform (MP). $r_b$is the radius of the base platform and r_e is the radius of the moving platform. In figures (2) and (3), γ is the angle between the connection points of BP i.e.$(b_1, b_2), (b_3, b_4), (b_5, b_6)$and the connection points of MP i.e.$(a_1, a_6), (a_2, a_3), (a_4, a_5)$. The angle between the connection points of BP is shown by γ_bThe angle between the connection points of MP is shownby γ_e.

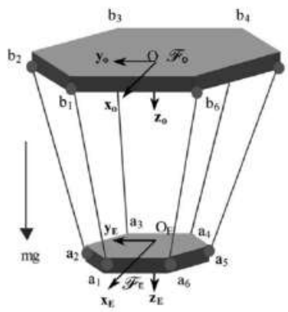

Figure 2 structure of six-degree of freedom cable robot

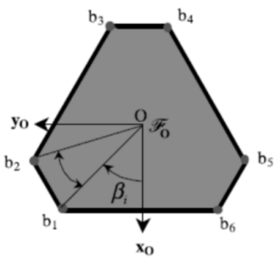

Figure (2) view of the base platform

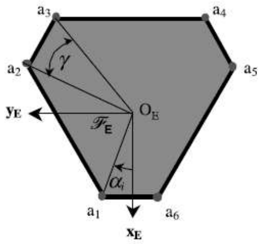

Figure (3) view of the moving platform

State vector of the point O_{b_i} on the base is defined as follows:

$$(1) \qquad O_{b_i} = \begin{bmatrix} r_b \cos\beta_i \\ r_b \sin\beta_i \\ 0 \end{bmatrix}$$

Variable β_i indicates the angular position of point b_i on BP relative to axis x_0 shown in Figure 2.
Position vector of the connectionpoints on the moving platform is as follows:

$$(2) \quad E_{a_i} = \begin{bmatrix} r_e \cos\alpha_i \\ r_e \sin\alpha_i \\ 0 \end{bmatrix}$$

Variable β_i indicates the angular position of the connection points on MP relative to x_E shown in Figure 3.
The vector diagram of the model is shown in Figure 4. As it is clear the state vector from b_i to a_i defined as the vector of the cable length relative to the fixed frame F_O is expressed as follows:

$$(3) \quad o_{l_i} = o_{p_E} + [R]^M E_{a_i} - O_{b_i}, \quad i = 1,2,\dots,6$$

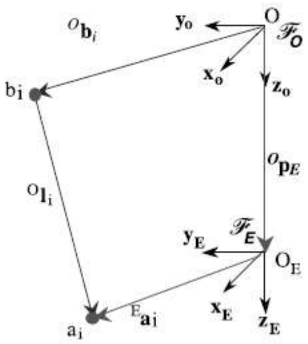

Figure.4 vector diagram of the robot

O_{b_i} is the state vector of connection points on the base platform

E_{a_i} is the position vector of connection points on the moving platform

O_{p_E} is the state vector of point O_E relative to O

Rotation matrix MP relative to BP is written by three angles of ψ, θ and φ, , around the axis of z_0, y_0, x_0, respectively, as the following equation:

(4)

$$[R] = \begin{bmatrix} \cos\varphi\cos\theta & -\sin\varphi\cos\psi + \cos\varphi\sin\theta\sin\psi & \sin\varphi\sin\psi + \cos\varphi\sin\theta\cos\psi \\ \sin\varphi\cos\theta & \cos\varphi\cos\psi + \sin\varphi\sin\theta\sin\psi & -\cos\varphi\sin\psi + \sin\varphi\sin\theta\cos\psi \\ -\sin\theta & \cos\theta\sin\psi & \cos\theta\cos\psi \end{bmatrix}$$

The length of each cable is defined as follows:

$$(5) \quad l_i = \left\| o_{l_i} \right\|^2 = o_{l_i}^T o_{l_i}$$

The Jacobian matrix of the cable robot is calculated forthe i_{th} row as follows:

$$(6) \quad j_i = \left[\left(\frac{o_{l_i}}{l_i}\right) \quad \left(o_{a_i} \times \frac{o_{l_i}}{l_i}\right) \right]$$

i=1,2,...,6

(7) $o_{a_i} = [R]^M E_{a_i}$

Workspace analysis
To analyze robot workspace, the force of the cable must be determined at any point in the search space and if all cables are in positive traction mode the analysis will be done at that point. Thus, to find the force of the cable, the static equilibrium of the parallel robot is used. The equilibrium of force and torque in moving platform is expressed as follows:

(8) $\sum F_x = 0, \sum F_y = 0, \sum F_z = mg$
$$\sum M_x = 0, \sum M_y = 0, \sum M_z = 0$$

It is observed that notorque is applied on the moving platform and the only external force is the gravity. In fact, it assumes that no external force is applied on the system other than the gravity and as the result other external forces and torques are negligible. By relating external forces shown in equation (8) to the cable forces, the reciprocal relationship between the kinematic and static is achieved:

(9)$F_{ext} = J^T s$
Cable traction vector s is expressed as follows:

$$s = [s_1 s_2 s_3 s_4 s_5 s_6]^T$$
$F_{ext}$is the six-dimensional vector containing the external forces and torques applied to the final implementation, and we have:
$$F_{ext} = [F_x F_y F_z M_x M_y M_z]^T$$

The first three components are the forces used and the second three components are used torques for MP.
Now, to obtain cable force equation, equation (9) is rewritten as follows:

(10)$s = J^{-T} F_{ext}$
In this equation, ifthe traction vector of every six cables is positive, the workspace of the cable robot is specified. Workspace volume is the set of points, in which the center of mass of the moving platform can be placed.

The kinematic index GCI
The performance quality of the robot with regard the force and the speed of transfer can be demonstrated using the Jacobian matrix condition number. The condition number is obtained according to the following equation:
(11) $k = \frac{\sigma_1}{\sigma_n}$
The numerator is the largest singular value and the denominator is the smallest singular value. Condition number value ranges between 1 and + ∞.When the condition number is getting close to 1 it means that theJacobian matrix has the desired condition and when the condition number is getting close to infinity,it means that the Jacobian matrix does not have the desired condition.Due to the intangibility of the range,the inverse of the condition number is used as kinematic condition index ranging between zero and one, and as the parameter is approaching to zero it is getting close to the singularity range and singular values.

(12) $$KCI = \frac{1}{K}, 0 < KCI < 1$$

This index is a local measure that is defined at any position of the robot it means that it is determined with regard to the Cartesian coordinates of the robot and its rotation around the Euler axis. To evaluate the overall performance of the robot, a general criterion of skill is expressed as mean condition index in the whole workspace and defined as general condition index as follows:

(13) $GCI = \frac{\Sigma(\frac{1}{k})}{v}$

The numerator isthe sum of condition number inverse in workspace configuration and the denominator is the number of points in the workspace.

Simulation

As said in the introduction of this chapter, after the underlying modeling and workspace analysis, the workspace volume and GCI are simulated for different geometric configurations, different ratios of MP to BP and different directionsof moving platforms (MP) using MATLAB software. The software includes connection points ofbase and moving platforms, the radius of these points on both platforms, the direction of the moving platform, the desired search volume and development of step size for network exploration (mesh) is. To maintain the consistency, the step size is fixedon 0.1.Search volume of the workspace has been considered in the area ≥-6$x_0 \leq 6, -6 \leq y_0 \leq 6, 0 \leq z_0 \leq 10$)and finally $r_b = 6$ is assumed.

Different geometric configurations

In the studied simulation, as instance, two different geometric designs were studied and compared. The designs include geometric configuration of$\gamma = 45^{\circ}$ and $\gamma = 0^{\circ}$configured as half a symmetrical hexagonal and an equilateral triangle, respectively like three-degree of freedom Stewart platform. In this study, the geometric difference of BP compared to MP is not examined due to the mismatch of angle γ for both base and moving platforms.

2.5. Different proportions of fixed and movingplatforms

The analysis is conducted for three different proportions $\frac{r_e}{r_b} = 1\%, 50\%, 100\%$and based on the Euler angles shown in Table (1), and only some of the diagramsare presented in this paper.

Table.1 sets of directions

Degree	
0,10,20,30,330,340,330	ψ
θ	0,10,20,30,330,340
φ	0,10,20,30,40,50,60,300,310,320,330,340,350

For example, the diagram of workspace volume changes for the geometry of the γ = 0 and constant direction of φ= 20° for various ratios of BP to MP is plotted in figure (5).

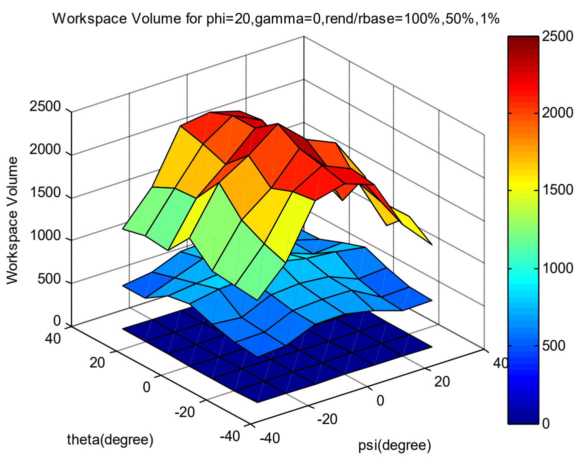

Figure.5 workspace volume for $\varphi = 20^{\circ}, \gamma = 0, \frac{r_e}{r_b} = 1\%, 50\%, 100\%$

Similarly, the diagram of GCI changes for the geometry of $\gamma = 0$ and the constant direction of for constant of $\varphi = 20^{\circ}$ for different proportions ofMP to BP is plotted in figure (6).

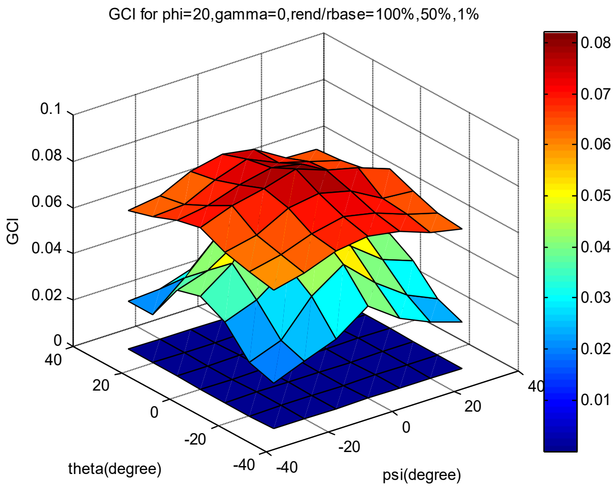

Figure (6) GCI for $\varphi = 20^{\circ}, \gamma = 0, \frac{r_e}{r_b} = 1\%, 50\%, 100\%$

Due to the extensivedata of some observed directions and in order to reduce it, the mean sample size has been used. In this case, for each given geometry and proportion of MP to BP, fordifferent poses of ψ, θ with angular step of 10 degrees related to each constant value of φ in the given range in Table 1, allvalues of the workspace are averaged. Findings can be observed in different values of φ in Fig 7 and Fig 8.

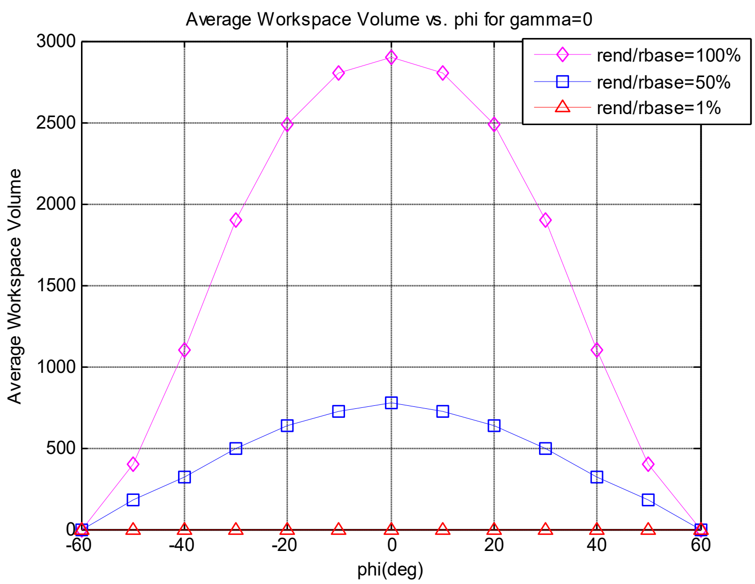

Figure (7) mean workspace volume according to φ for the geometry of γ = 0 °

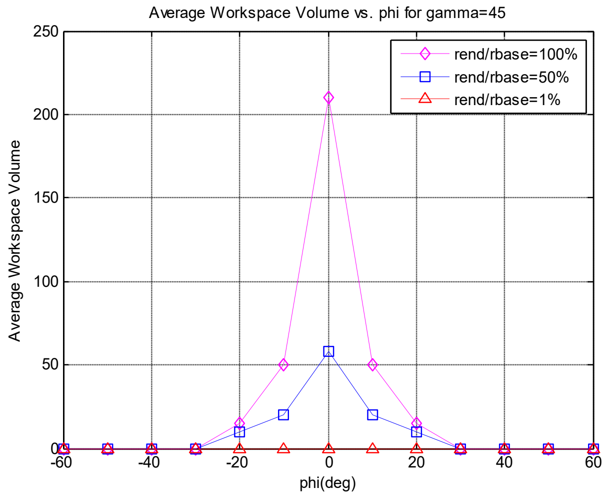

Figure (8) mean workspace volume according to φ for the geometry of γ =45 °

As can be seen in Figure 7 and Figure 8 show, by increasing the ratio of MP to BP, the mean workspace volume increases so $\frac{r_e}{r_b} = 100\%$ has thehighest workspace volume and $\frac{r_e}{r_b} = 1\%$has the lowest value. Similarly, with respect to the different directions of ψ, θ for each constant value of φ and each geometry and size, all values of GCI are averaged that the results can be seen in Figure 9 and Figure 10. As can be seen, the value of GCI is slowly increasing from φ = 0°, then decreases gradually up to φ = ± 60 °.

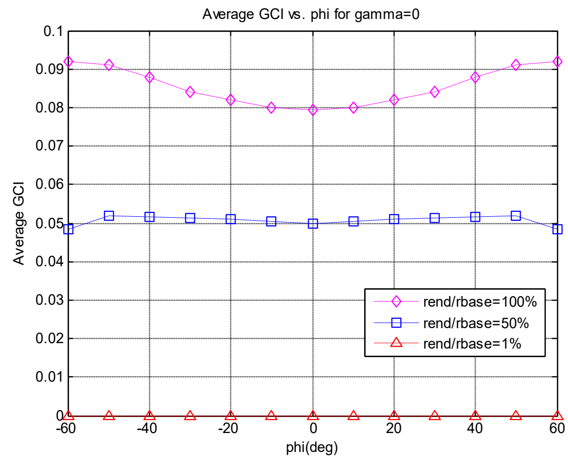

Figure (9) mean values of GCI based on φ for the geometry of γ = 0°

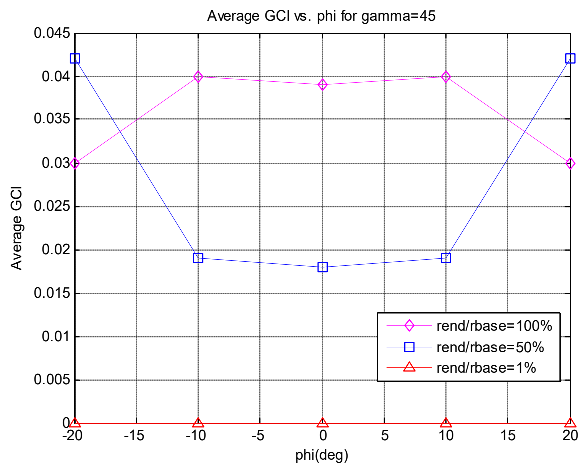

Figure (10), the average size of the workspace according to φ for the geometry of γ =45°

CONCLUSION

This paper discusses the design and the analysis of six-degree of freedom cable robot workspace for a particular motion of the moving platform. In this regard, changes in the size of the workspace and kinematic index GCI were examined based on two samples of different geometric configurations, three different ratios of movingplatform to base platformfor a special motion of the moving platform. The results indicate that, for the geometry of the robot, the largest workspace volume occurs when the moving platform is the same size as the base platform. In other words, for the geometry $\gamma = 0$ the robot has the maximum workspace and the highest general condition index. The results obtained can be used as a general rule when designing this type of robots.

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