3D cable-based parallel robot simulation using PD control

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Abstract. In this paper, we present a simulator that has been developed using PD control to study 3D cable-based parallel robot with four cables. The proposed control technique is widely used for dealing with linear systems uncertainties, in this context; we investigated to use the Runge Kutta method of 4th order for solving non-linear partial differential equations of our system. The main contribution of this work is firstly: modelling of differential equations of our system. Secondly, the PD control applied to the dynamic model for different trajectories in order to test the accurate tracking of the robot to a desired trajectory. The effectiveness of the proposed control strategy is improving the robot performance in terms of tracking a desired path.

Keywords. Cable based robot; Modelling; PD control; GUI; Runge Kutta Method.

1. Introduction

Automation and robotic becoming more important due to demanding on cost effective operations and productivity improvement in nowadays [1-3] due to the energy and fuel resources are in pressing for supply and sustainability issue [4-7]. Cable-based parallel robots are a special parallel manipulators robot in which the end-effectors are driven by cables instead of rigid links [2, 8, 9], the movement being provided by the winding and unwinding of cables [10, 11]. This offer incontestable advantages in comparison to the robots of classic architecture, tis last it is a type of parallel manipulator used as a transmission way of cables connects a fixe base with a mobile platform. The coordinate controller of cable lengths and tensions permit the displacement and the application of efforts on the platform. These robots have few moving parts, with reduced mass, and are most suitable for tasks requiring high performance such as speed and accuracy and provide a large workspace. By moving the cables connections points, it is possible to obtain reconfigurable manipulators. In addition, they are easy to mount; dismount and transport, in other hand, the main disadvantages of parallel manipulators lie in the nature of the cables that can only work in one direction than the traction [12-14]. The best-known application is the Skycam, a camera controlled by a cables mechanism that is used for tele-diffusion of professional football games. Another area of interest in biomedical applications such as tracking the movement of body parts. An example is the CaTraSys (Cassino Tracking System) was used for the identification of kinematic parameters and the mobility of man [15, 16].

One of the key aspects for cable driven robots is the need of a proper control strategy to achieve proper motions without breaking the cables. The PD method has been designed to improve the

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robustness of robotic system control, as reported for example in [17-19]. In particular, an adaptive PD controller can adjust the control torque based on real-time position tracking error in the set-point control of the end-effector. The aim of this work is an simulation results of cables based robot permitting to digitalize the appearance 3D for four cables with kinematics modelling, followed by statics modelling, then presents dynamics modelling implement their command in close loop with PD controller. We adopt the system using eight cables presented in Gallina, Rossi and Williams II [20].

2. System overview

Figure 1 shows our virtual prototype robot with four cables. The base is fixed and each cable attached to the one end of the platform. As the result of motors moments, cable wraps and winds the cables around the pulley to control the position and the orientation of the end-effector. The four cables-based robots allow a plan movement with 4 degrees of freedom.

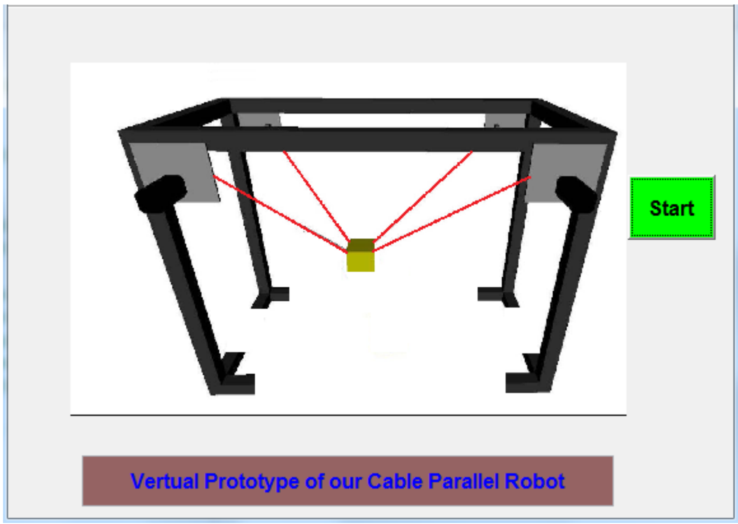

Figure 1. A virtual prototype of 3D driven parallel robot.

3. Geometric modelling

In this section, we present the direct and inverse geometric model for three and four cable-based robots.

3.1. Inverse geometric model (IGM)

This model aims to determine the lengths of the cables "Li", the angles "Θi" between the X,Y axes and the cables connected to the mobile platform and "αi" between the Z axe the plane X, Y. The inverse geometric model can be expressed by the following equations [21].

$$Li = \sqrt{(x - Aix)^2 + (y - Aiy)^2 + (z - Aiz)^2} \quad ; \text{i=1...n} \tag{1}$$

$$\Theta i = \arctan g(\frac{y - Aiy}{x - Aix}) \quad ; \text{i=1...n} \tag{2}$$

$$\alpha i = \arctan g(\frac{z - Aiz}{\sqrt{(x - Aix)^2 + (y - Aiy)^2}}) \quad ; \text{i=1...n} \tag{3}$$

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4. The dynamic response of our system with a pd controller

In this section, we begin by presenting the dynamic equation of the robot with five and eight cables and its state-space representation. Then, the response will be simulated in closed loop with PD controller [22] .

4.1. Dynamic model of the end effector

The dynamic model of the actuator is expressed by the following relationship [23]:

$$m\ddot{X} = F_R \tag{4}$$

Where: m is the mass matrix and $\ddot{X}$ is the acceleration vector of the end-effector. $F_R = \begin{pmatrix} F_{Rx} & F_{Ry} & F_{Rz} \end{pmatrix}^T$: is the resultant force of the all tensions applied to the cables.

Where:

$$\begin{pmatrix} m & 0 & 0 \\ 0 & m & 0 \\ 0 & 0 & m \end{pmatrix} \begin{pmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \end{pmatrix} = \begin{pmatrix} F_{Rx} \\ F_{Ry} \\ F_{Rz} \end{pmatrix} \tag{5}$$

4.1.1. The dynamic comportment of the motor. The dynamic comportment of the motor can expressed by the following equation according to structure pulley as illustrated in figure 2.

$$J\ddot{\beta} + C\dot{\beta} = \tau - rT. \tag{6}$$

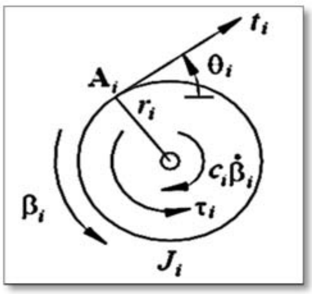

Figure 2. Structure pulley.

with:

$$Jmat = \begin{pmatrix} J_1 & 0 & 0 & 0 & 0 \\ 0 & J_2 & 0 & 0 & 0 \\ 0 & 0 & J_3 & 0 & 0 \\ 0 & 0 & 0 & J_4 & 0 \\ & & & & \end{pmatrix} \text{ et } Cmat = \begin{pmatrix} C_1 & 0 & 0 & 0 & 0 \\ 0 & C_2 & 0 & 0 & 0 \\ 0 & 0 & C_3 & 0 & 0 \\ 0 & 0 & 0 & C_4 & 0 \\ & & & & \end{pmatrix} \tag{7}$$

We consider that all the rays of the pulley are the same, ri = r(i=1.2...4), $\tau\ (\tau_1.\tau_2,...\tau_i)^T$ is the vector of the torques applied by the motors. t(t1,t2,…ti)T is the vector of tension cables. β is the angle of rotation of the pulley. So:

$$t = \frac{1}{r}(\tau - J\ddot{\beta} - C\dot{\beta}) \tag{8}$$

Where Li0 are the initial lengths of the cables: $L_{i0} = \sqrt{(Aix)^2 + (Aiy)^2 + (Aiz)^2}$
So,

$$\beta = \begin{pmatrix} \beta_1(X) \\ \beta_2(X) \\ \vdots \\ \beta i(X) \end{pmatrix} = \frac{1}{r}\begin{pmatrix} L_{10} - L_1 \\ L_{20} - L_2 \\ \vdots \\ L_{i0} - L_i \end{pmatrix} \tag{9}$$

i=1,.. ,*4*

$$\dot{\beta} = \frac{\partial\beta}{\partial x}\dot{x} = -\frac{1}{r}\left[\begin{pmatrix} \cos(\alpha_1)\cos(\Theta_1) & \cos(\alpha_1)\sin(\Theta_1) & \sin(\alpha_1) \\ \cos(\alpha_2)\cos(\Theta_2) & \cos(\alpha_2)\sin(\Theta_2) & \sin(\alpha_2) \\ \cos(\alpha_3)\cos(\Theta_3) & \cos(\alpha_3)\sin(\Theta_3) & \sin(\alpha_3) \\ \cos(\alpha_4)\cos(\Theta_4) & \cos(\alpha_4)\sin(\Theta_4) & \sin(\alpha_4) \\ \sin(\alpha_5)\cos(\Theta_5) & \sin(\alpha_5)\sin(\Theta_5) & \cos(\alpha_5) \end{pmatrix}\begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{pmatrix}\right] \tag{10}$$

by subtracting successively (10) with respect to time, we get:

$$\ddot{\beta} = \frac{d}{dt}\left(\frac{\partial\beta}{\partial x}\right)\dot{x} + \frac{\partial\beta}{\partial x}\ddot{x} \tag{11}$$

Substituting (11) we obtain:

$$t = \frac{1}{r}\left(\tau - J\left(\frac{d}{dt}\left(\frac{\delta\beta}{\delta X}\right)\dot{X} + \frac{\delta\beta}{\delta X}\ddot{X}\right) - C\frac{\delta\beta}{\delta X}\dot{X}\right) \tag{12}$$

Finally, the set of equations of the dynamic model can be expressed in a standard form for robotic systems (13):

$$\ddot{X}(t) = M^{-1}(X) * N(X,\dot{X}) + M^{-1}(X) * S(X) * \tau \tag{13}$$

Where:

$$M = r * m + S(X)J\frac{\delta\beta}{\delta X} \tag{14}$$

And

$$N(X,\dot{X}) = S(X)(J\frac{d}{dt}\frac{\delta\beta}{\delta X} + C\frac{\delta\beta}{\delta X}\dot{X}) \tag{15}$$

$$\tau = \begin{bmatrix} \tau_1 \\ \tau_2 \\ \cdot \\ \cdot \\ \tau_i \end{bmatrix} \tag{16}$$

5. Control law and architecture

This section presents our control architecture and the low-level control has been ensured by means of the implementation of a Proportional and Derivative (PD) controller based on the overall system Cartesian dynamics equations of motion (Equation 16). Williams, Gallina and Vadia [24] in his paper on the PD controller gains are determined the error using a MatLab programmed simulation to achieve reasonable performance for the trajectories. The establishment of the control law along X,Y and along Z is:

$$\begin{cases} U_X = K_P e_X(t) + K_D \dot{e}_X(t) \\ U_Y = K_P e_Y(t) + K_D \dot{e}_Y(t) \\ U_z = K_P e_z(t) + K_D \dot{e}_z(t) \end{cases} \tag{17}$$

The control architecture as shown in figure 3 was made up of three different parts: the PD controller, the tension calculation and pulley angle β to determine the cable lengths L_i.

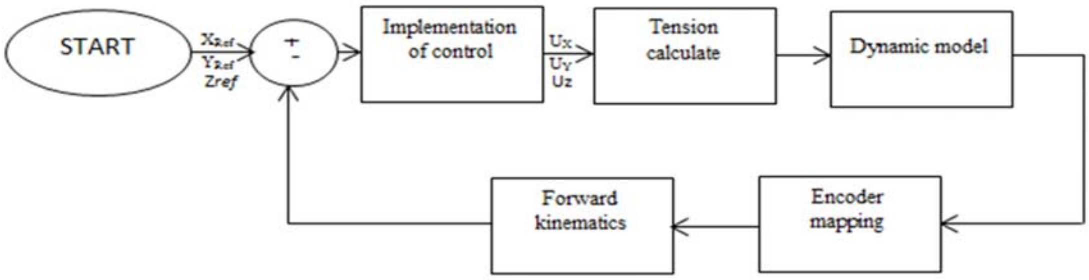

Figure 3. Control architecture.

6. Simulation results

In this part, we present the simulation of the response for 3D cables-based robot with 4 cables, for dynamic equation, which has a non-linear equation system, for this purpose, we use a Runge Kutta method as a numeric solution. Runge and Kutta developed the following formulae [25]:

$$y(x_1) \approx y_0 + (k_1 + 2k_2 + 2k_3 + k_4)/6, \tag{18}$$

$$k_1 = hf_o, , f_o \approx f(x_0, y_0) \tag{19}$$

$$k_2 = hf(x_0 + h/2, y_o + k_1/2) \tag{20}$$

$$k_3 = hf(x_0 + h/2,\ y_0 + k_2/2) \tag{21}$$

$$k_4 = hf(x_0 + h,\ y_0 + k_3) \tag{22}$$

Then, we implement a Cartesian PD controller in this dynamic equation for reduce the tracking error ($e = X_{desired} - X_{actual}$). The parameters for the dynamics equations of motion (15) for the 5 and 8 cables are: point mass m = 0.01 kg; rotational shaft/pulley inertias Ji (i = 1,…,4) = 0.0008 kgm2; shaft rotational viscous damping coefficients Ci (i = 1,.., 4) = 0.01 Nms and ri = r = 1cm (for all i = 1,…, 4 or 8) and a the side of square basis and the cubic is Lb = 0.6580 m and the values of coefficient for different trajectories are Kp=25000 , Kd=1850, So we put the reference of our system in the centre of the workspace (0,0,0). Figure 4 until figure 7 shows a graphical user interface of implementation the point-to-point command i.e the user of this interface can enter the coordinates of any point into the workspace. When clicked on the plot, the end effector displaced directly to this point with a high precision, and also, this interface can initialization the case of this robot (figure 7), these technique based on inverse geometric model.

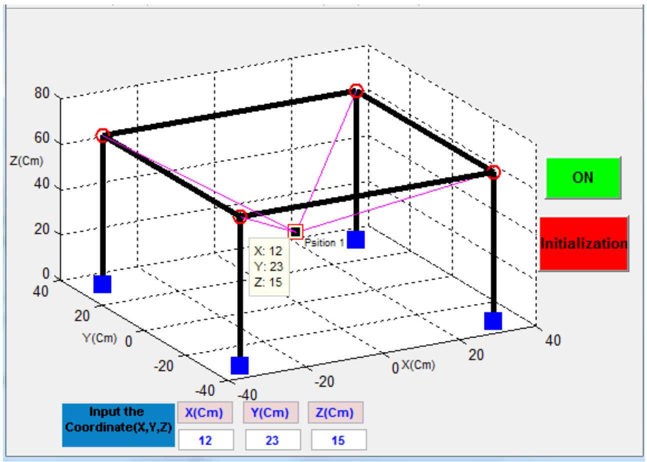

Figure 4. Plot the displacement the end effector to position one.

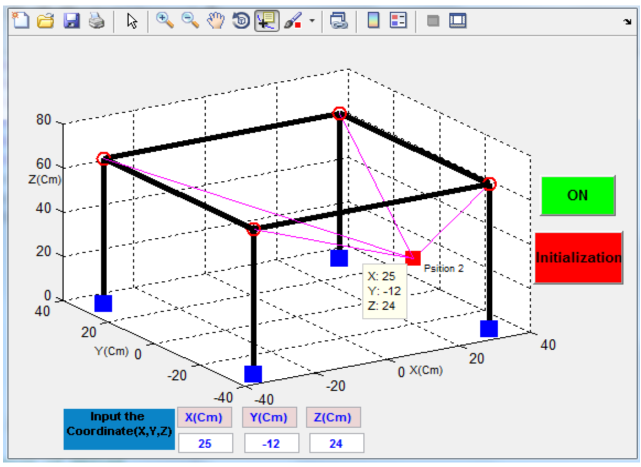

Figure 5. Plot the displacement the end effector to position two.

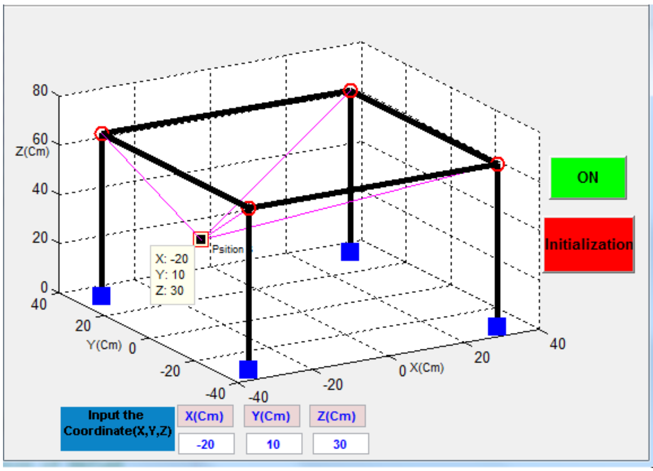

Figure 6. Plot the displacement the end effector to position tree.

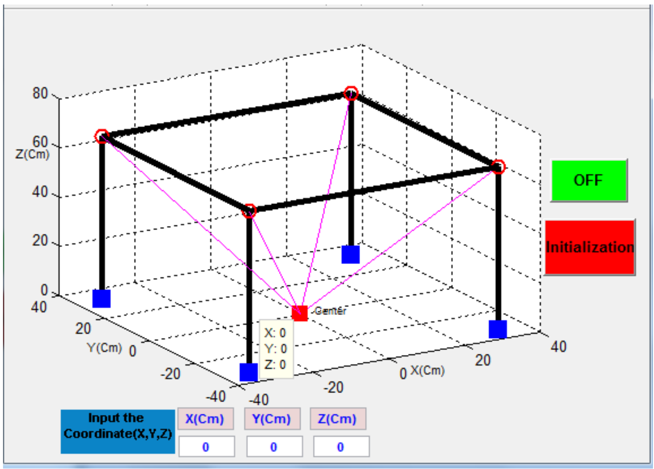

Figure 7. Meter the end effector on initial position.

For illustrating the role of our control, we use another interface graphic command according to the colours of the objects. When, we have clicked on colour object, the end effector move and displace to this object in workspace. Figure 8, 9, 10 and 11 show how to control the end effector based on the colour objects, and also, this interface can draw the trajectory of end effector, that do for different tests (figure 12), this technique based on the kinematic and dynamic model for this robot. The results of different tests carried that, this PD control give a better performance in most operation conditions.

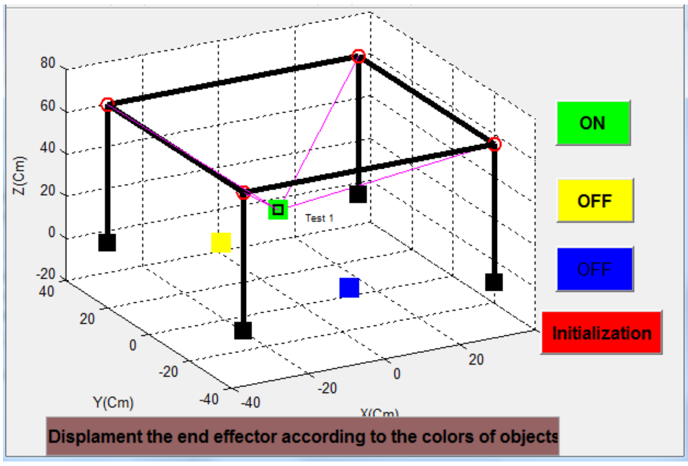

Figure 8. Displacement the end effector according to the green colour.

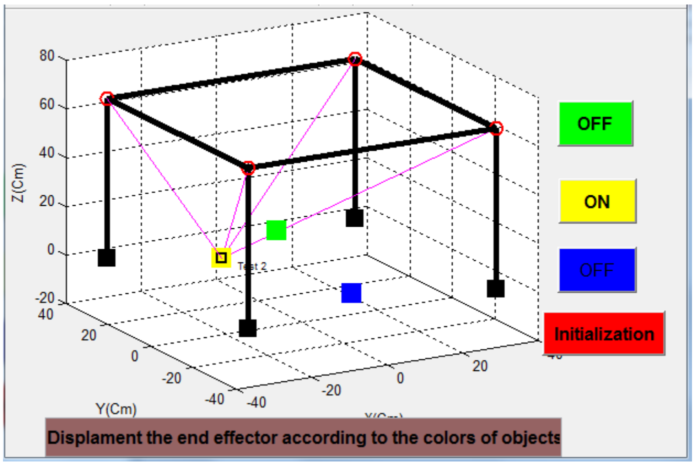

Figure 9. Displacement the end effector according to the yellow colour.

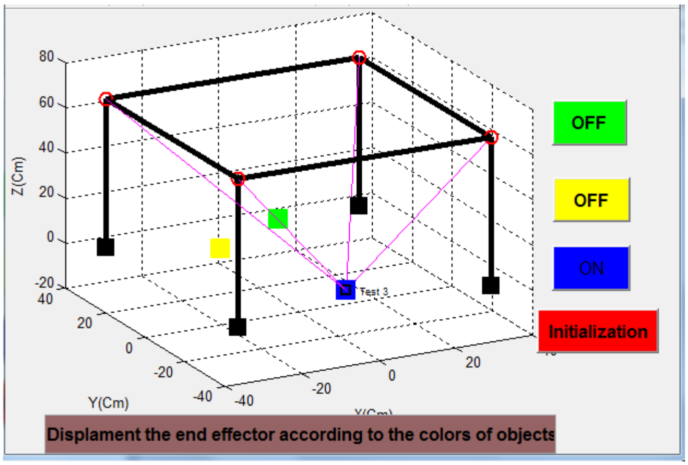

Figure 10. Displacement the end effector according to the blue colour.

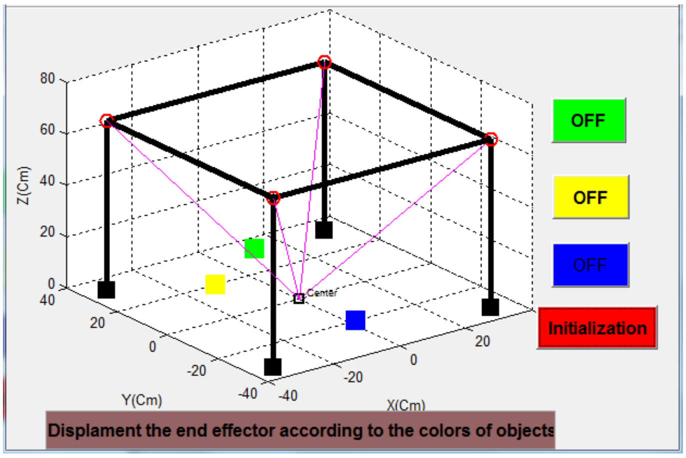

Figure 11. Initialization the parameters of position of end effector.

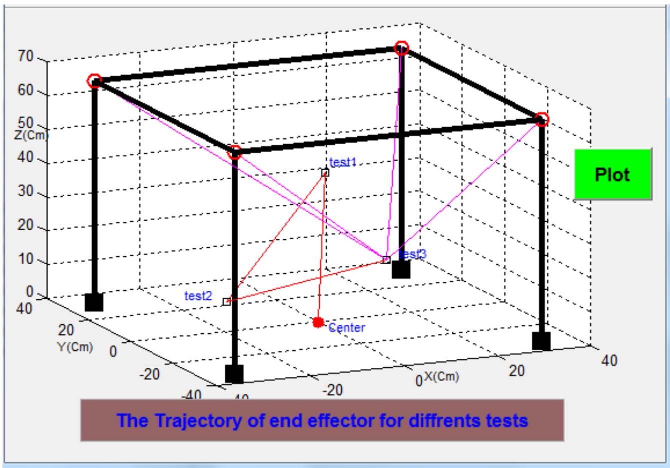

Figure 12. The trajectory of end effector for different tests.

For more illustrate the role of our control, we simulate the continuance trajectories, figure 13 and 14 show that, how the real path follows the desired path for the ellipse and circular trajectories. The ellipse trajectories in Fig. 13 shows that the desired and actual path is almost agreed with each other. The actual path is in good agreement with the desired path. This shows the simulation and the control is very good results. Similar results found in figure 14 for the circular trajectories. Compare both circular path for actual and desired are almost identical movement.

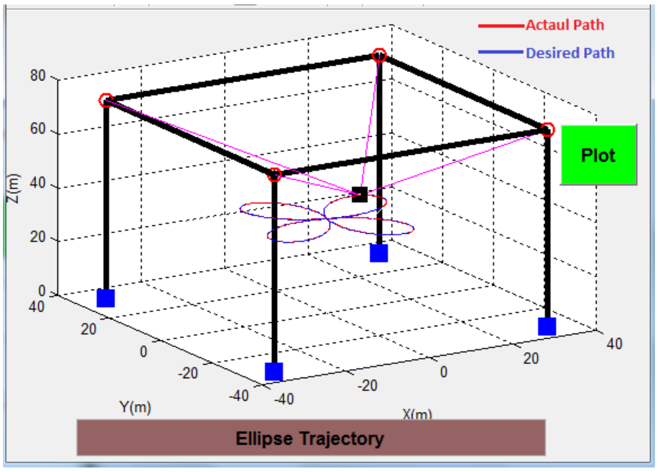

Figure 13. Plot the desired path and actual for ellipse trajectory.

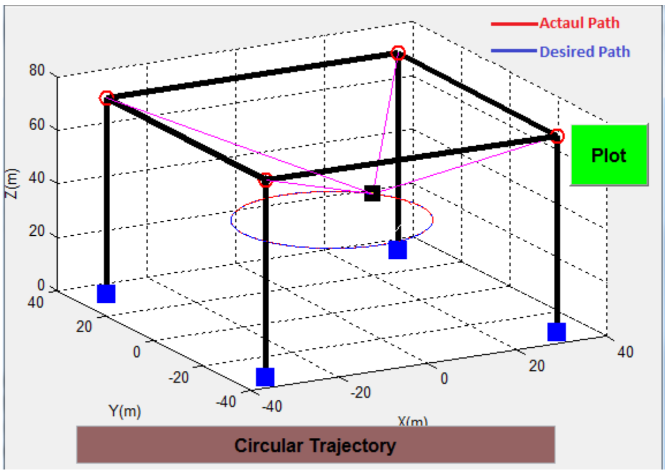

Figure 14. Plot the desired path and actual for circular trajectory.

As seen in the different tests of the point to point command and the tests for displacement the end effector according the colour objects and also the tests of follow predefined trajectories for actual and desired paths, we found that, the PD controller do a high role and efficacy of the precision for 3D cable base robots.

7. Conclusion

This paper presented a simulation results for different tests of a novel 3D cable base robot with four cables, this last, we have developed a user interface graphic with a simulation program to control the displacement of end effector based on point to point command, according to the colour of the objects and also, we have presented some results for continuance trajectories. The simulation results have demonstrated the effectiveness and feasibility of the proposed control and suitable for improving the performance response.

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