3D cable-based parallel robot simulation using PD control

F Inel¹ and M M Noor²
¹ Department of Mechanical Engineering, Automatic Laboratory, University of Skikda, Algeria
² Faculty of Mechanical & Manufacturing Engineering, University of Malaysia Pahang, Malaysia, 26600 Pekan, Malaysia

*corresponding author: inelfouad@yahoo.fr

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
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.

![Virtual Prototype of 3D Driven Parallel Robot](image)

**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].

\[
Li = \sqrt{(x - Aix)^2 + (y - Aiy)^2 + (z - Aiz)^2} ; i=1...n
\]  

\[
Θi = \arctan \left( \frac{y - Aiy}{x - Aix} \right) ; i=1...n
\]  

\[
αi = \arctan \left( \frac{z - Aiz}{\sqrt{(x - Aix)^2 + (y - Aiy)^2}} \right) ; i=1...n
\]
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]:

\[ m \ddot{X} = F_R \]  

(4)

Where: \( m \) is the mass matrix and \( \dot{X} \) is the acceleration vector of the end-effector. \( F_R = \begin{bmatrix} F_{Rx} & F_{Ry} & F_{Rz} \end{bmatrix} \) is the resultant force of the all tensions applied to the cables.

\[
\begin{pmatrix}
  m & 0 & 0 \\
  0 & m & 0 \\
  0 & 0 & m
\end{pmatrix}
\begin{bmatrix}
  \ddot{x} \\
  \ddot{y} \\
  \ddot{z}
\end{bmatrix} = 
\begin{bmatrix}
  F_{Rx} \\
  F_{Ry} \\
  F_{Rz}
\end{bmatrix}
\]  

(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.

\[ J \ddot{\beta} + C \dot{\beta} = \tau - rT. \]  

(6)

Figure 2. Structure pulley.

with:

\[ J_{mat} = \begin{pmatrix}
  J_1 & 0 & 0 & 0 & 0 \\
  0 & J_2 & 0 & 0 & 0 \\
  0 & 0 & J_3 & 0 & 0 \\
  0 & 0 & 0 & J_4 & 0
\end{pmatrix} \quad \text{et} \quad C_{mat} = \begin{pmatrix}
  C_1 & 0 & 0 & 0 & 0 \\
  0 & C_2 & 0 & 0 & 0 \\
  0 & 0 & C_3 & 0 & 0 \\
  0 & 0 & 0 & C_4 & 0
\end{pmatrix} \]  

(7)
We consider that all the rays of the pulley are the same, $r_i = r (i=1,2,...4)$, $\tau (\tau_1, \tau_2, ..., \tau_4)^T$ is the vector of the torques applied by the motors. $t(t_1, t_2, ..., t_i)^T$ is the vector of tension cables. $\beta$ is the angle of rotation of the pulley. So:

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

(8)

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

So, $\beta = \begin{bmatrix} \beta_1(X) \\ \beta_2(X) \\ \vdots \\ \beta_i(X) \end{bmatrix} = \frac{1}{r} \begin{bmatrix} L_{i0} - L_1 \\ L_{i0} - L_2 \\ \vdots \\ L_{i0} - L_i \end{bmatrix}$

(9)

$$i=1,...,4$$

$$\dot{\beta} = \frac{\partial \beta}{\partial x} \dot{x} = -\frac{1}{r} \begin{bmatrix} \cos(\alpha_1) cos(\Theta_1) & \cos(\alpha_1) sin(\Theta_1) & sin(\alpha_1) \\ \cos(\alpha_2) cos(\Theta_2) & \cos(\alpha_2) sin(\Theta_2) & sin(\alpha_2) \\ \cos(\alpha_3) cos(\Theta_3) & \cos(\alpha_3) sin(\Theta_3) & sin(\alpha_3) \\ \cos(\alpha_4) cos(\Theta_4) & \cos(\alpha_4) sin(\Theta_4) & sin(\alpha_4) \\ sin(\alpha_1) cos(\Theta_1) & sin(\alpha_1) sin(\Theta_1) & cos(\alpha_1) \\ \sin(\alpha_2) cos(\Theta_2) & \sin(\alpha_2) sin(\Theta_2) & cos(\alpha_2) \\ \sin(\alpha_3) cos(\Theta_3) & \sin(\alpha_3) sin(\Theta_3) & cos(\alpha_3) \\ \sin(\alpha_4) cos(\Theta_4) & \sin(\alpha_4) sin(\Theta_4) & cos(\alpha_4) \end{bmatrix} \begin{bmatrix} x^* \\ y^* \\ z^* \end{bmatrix}$$

(10)

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

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

(11)

Substituting (11) we obtain:

$$t = \frac{1}{r} \left( \tau - J \left( \frac{d}{dt} \left( \frac{\partial \beta}{\partial x} \right) \ddot{x} + \frac{\partial \beta}{\partial x} \dddot{x} \right) - C \frac{\partial \beta}{\partial x} \dddot{x} \right)$$

(12)

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

$$\dddot{X(t)} = M^{-1}(X) \cdot N(X, \ddot{x}) + M^{-1}(X) \cdot S(X) \cdot \tau$$

(13)

Where:

$$M = r \cdot m + S(X) J \frac{\partial \beta}{\partial x}$$

(14)

And
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:

\[
N(X, \dot{X}) = S(X) \left( J \frac{d}{dt} \frac{\delta \theta}{\delta X} + C \frac{\delta \theta}{\delta X} \right) \tag{15}
\]

\[
\tau = \begin{bmatrix}
\tau_1 \\
\tau_2 \\
\vdots \\
\tau_4
\end{bmatrix} \tag{16}
\]

5. Control law and architecture

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

\[
\begin{aligned}
U_X &= K_P e_X(t) + K_D \dot{e}_X(t) \\
U_Y &= K_P e_Y(t) + K_D \dot{e}_Y(t) \\
U_Z &= K_P e_Z(t) + K_D \dot{e}_Z(t)
\end{aligned} \tag{17}
\]

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]:

\[
y(x_i) = y_0 + (k_1 + 2k_2 + 2k_3 + k_4)/6, \tag{18}
\]

\[
k_1 = hf_{x_i} f_0 \approx f(x_0, y_0) \tag{19}
\]

\[
k_2 = hf(x_0 + h/2, y_0 + k_1/2) \tag{20}
\]
\[ k_3 = hf(x_0 + h/2, y_0 + k_2/2) \]  \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 \( e = X_{\text{desired}} - X_{\text{actual}} \). The parameters for the dynamics equations of motion (15) for the 5 and 8 cables are: point mass \( m = 0.01 \text{ kg} \); rotational shaft/pulley inertias \( J_i (i = 1,...,4) = 0.0008 \text{ kgm}^2 \); shaft rotational viscous damping coefficients \( C_i (i = 1,...,4) = 0.01 \text{ Nms} \) and \( r_i = r = 1\text{ cm} \) (for all \( i = 1,...,4 \) or 8) and a the side of square basis and the cubic is \( L_b = 0.6580 \text{ m} \) and the values of coefficient for different trajectories are \( K_p=25000, K_d=1850 \), 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.](image_url)

![Figure 5. Plot the displacement the end effector to position two.](image_url)
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.

Acknowledgements
The authors would like to thank to the University of Skikda, Algeria and Universiti Malaysia Pahang (UMP) for the resources and laboratory supported to the project.
References
[1] Zhang J, Fang X and Qi L 2016 Sensitivity-analysis based method in single-robot cells cost-effective design and optimization Robotics and Computer-Integrated Manufacturing 38 9-15
[2] Inel F, Mansouri Z, Cecarelli M and Carbone G 2018 New Advances in Mechanism and Machine Science: Springer) pp 413-26
[3] Fernini B, Temmar M and Noor M M 2018 Toward a dynamic analysis of bipedal robots inspired by human leg muscles Journal of Mechanical Engineering and Sciences 12 3593-604
[4] Bonilla D 2009 Fuel demand on UK roads and dieselisation of fuel economyEnergy Policy 37 3769-78
[5] Safieddin Ardebili M, Ghobadian B, Najafi G and Chegeni A 2011 Biodiesel production potential from edible oil seeds in Iran Renewable and Sustainable Energy Reviews 15 3041-4
[6] Noor M M, Wandel A P and Yusaf T 2014 MILD combustion: The future for lean and clean combustion technology International Review of Mechanical Engineering 8 251-7
[7] Bonilla S, Silva H, Terra da Silva M, Franco Gonçalves R and Sacomano J 2018 Industry 4.0 and sustainability implications: A scenario-based analysis of the impacts and challenges Sustainability 10 3740
[8] Zi B and Qian S 2017 Design, Analysis and Control of Cable-suspended Parallel Robots and Its Applications, (Singapore: Springer Singapore) pp 1-20
[9] Mottola G, Gosselin C and Carricato M 2019 Dynamically feasible motions of a class of purely-translational cable-suspended parallel robots Mechanism and Machine Theory 132 193-206
[10] Bruckmann T, Reichert C, Meik M, Lemmen P, Spengler A, Mattern H and König M 2018 Concept Studies of Automated Construction Using Cable-Driven Parallel Robots. In: Cable-Driven Parallel Robots, ed C Gosselin, et al. (Cham: Springer International Publishing) pp 364-75
[11] Ko S Y, Park J-O, Park S-H, Jung J W and Seon J A 2018 Cable-driven pararell robot capable of changing workspace. Google Patents)
[12] Williams II R L, Albus J S and Bostelman R V 2004 3D Cable-Based Cartesian Metrology System Journal of Robotic Systems 21 237-57
[13] Wang K, Lu Q, Chen B, Shen Y, Li H, Liu M and Xu Z 2019 Endovascular intervention robot with multi-manipulators for surgical procedures: Dexterity, adaptability, and practicability Robotics and Computer-Integrated Manufacturing 56 75-84
[14] Washabaugh E P, Guo J, Chang C-K, Remy C D and Krishnan C 2019 A portable passive rehabilitation robot for upper-extremity functional resistance training IEEE Transactions on Biomedical Engineering 66 496-508
[15] Ottaviano E, Cecarelli M, Toti M and Carrasco C A 2002 Catrasys (cassino tracking system): A wire system for experimental evaluation of robot workspace Journal of Robotics and Mechatronics 14 78-87
[16] Demirel M 2018 Design of hybrid cable-constrained parallel mechanisms for walking machines, Izmir Institute of Technology)
[17] Zi B, Duan B, Du J and Bao H 2008 Dynamic modeling and active control of a cable-suspended parallel robot Mechatronics 18 1-12
[18] Tao Y, Xie X and Xiong H 2019 Transactions on Intelligent Welding Manufacturing: Springer) pp 139-56
[19] Homayounzade M and Khademhosseini A 2019 Disturbance Observer-based Trajectory Following Control of Robot Manipulators International Journal of Control, Automation and Systems 17 203-11
[20] Gallina P, Rossi A and Williams II R L 2001 Planar cable-direct-driven robots, part ii: Dynamics and control. In: ASME. DECT2001 ASME Design Engineering Technical Conference. Pittsburgh: ASME Publisher, pp 1241-7
[21] Williams R L, Gallina P and Rossi A 2001 Planar cable-direct-driven robots, part i: Kinematics and statics. In: Proceedings of the 2001 ASME Design Technical Conference, 27th Design Automation Conference, pp 178-86

[22] Khosravi M A and Taghirad H D 2014 Dynamic modeling and control of parallel robots with elastic cables: singular perturbation approach IEEE Transactions on Robotics 30 694-704

[23] Williams II R L 2002 Parallel robot projects at ohio university. In: Workshop on fundamental issues and future research directions for parallel mechanisms and manipulators, Quebec City, Canada, pp 248-56

[24] Williams R L, Gallina P and Vadia J 2003 Planar Translational CableDirectDriven Robots Journal of Robotic Systems 20 107-20

[25] Vafaei A, Khosravi M A and Taghirad H D 2011 Modeling and control of cable driven parallel manipulators with elastic cables: Singular perturbation theory. In: International Conference on Intelligent Robotics and Applications: Springer) pp 455-64