The Objective Oriented Design of a CUBE Cable - based Parallel Robot for Arm Rehabilitation Tasks

FOUED INEL[1], MOHAMMED KHADEM[2], ABDELGHAFOUR SLIMANE TICH TICH[2]
[1]Mechanical Engineering Department, Automatic Laboratory,
University of Skikda,
ALGERIA

[2]Mechanical Engineering Department LGMM Laboratory,
University of Skikda,
ALGERIA

Abstract: - Rehabilitation robots have been employed for training of neural impaired subjects or for assistance of those with weak limbs. A cube, cable-based parallel robot with eight cables designed for assisting patients in upper-limb rehabilitation activities, with control over the end-location effector's while locking its rotation around the horizontal and vertical axes, the device has a lightweight structure that is simple to set up and use for home usage for both pre-determined and personalized exercises. In this context, we have limited the tensions of the cables (always positive) and the lengths of the robot do not exceed the workspace. In addition, the design's kinematic and dynamic studies are presented. The aim of this paper is to help the patient rehabilitate the upper limb in axes (y-z) and (x-y) with improved patient safety, such that the arm for the patient can move it in the two planes. The simulation exercises with solidworks and matlab software demonstrate the effectiveness of our proposed design.

Key-Words: - CBPR- rehabilitation exercises- Kinematic and dynamic model.

Received: May 11, 2022. Revised: August 13, 2023. Accepted: September 16, 2023. Available online: October 31, 2023.

1 Introduction

A cable-based parallel robot (CBPR) is a special type of parallel robot where cables replace rigid links. Comparing CBPRs to traditional parallel robots, this feature gives CDPRs valuable performances in terms of a large workspace, high payload, high speed, and acceleration, [1], [2], [3]. The high sensitivity of CBPRs, along with their ease of installation and reconfiguration, make them suitable for rehabilitation tasks.in this context, physical rehabilitation is the process of helping patients in regaining control over certain limbs following a protracted sickness or traumatic event, [4]. Specifically, rehabilitation of the upper limbs. Additionally, rehabilitation robots are typically outfitted with sensors that can quantitatively and continuously monitor the status and progress of each patient. As a result, various robotic rehabilitation devices are already accessible, [5], [6]. One of the most important components of cable-based robots is the requirement for a suitable control strategy in order to produce proper movements without breaking the cables. As mentioned in, [7], [8], the PD approach was created to increase the robustness of robotic system control. This PD controller, in particular, can adjust the control torque depending on real-time position tracking error in the end-effector set-point control, [9].

The majority of these robots have a massive construction and pricey components. To address these concerns, unique cable-based rehabilitation activities have been developed. The principal aim of this work is to help the patient rehabilitate the upper limb in horizontal and vertical planes with a maximum distance between the cables and the patient during the physiotherapy exercises, [10].

The structure of this paper is as follows: firstly in section one, we introduced a problem formulation for the design of rehabilitation tasks with cable based parallel robots. Secondly, we presented the geometric and dynamic study of our parallel robot with eight cables. Thirdly, presents optimization Process and some simulation results for rehabilitation exercises in the horizontal and vertical planes. Finally, some conclusions are given in the last section.

2 The Proposed Design

Figure 1 shows the proposed conceptual design as based on the fulfillment of specific purposes or needs. Figure 2a and Figure 2b show respectively the general geometrical parameters and the vector analysis that applies to a part of the robot.

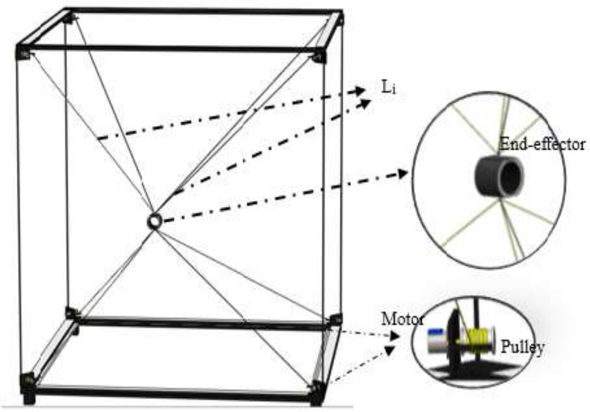


Fig. 1: The proposed design for CUBE - cable based parallel robot

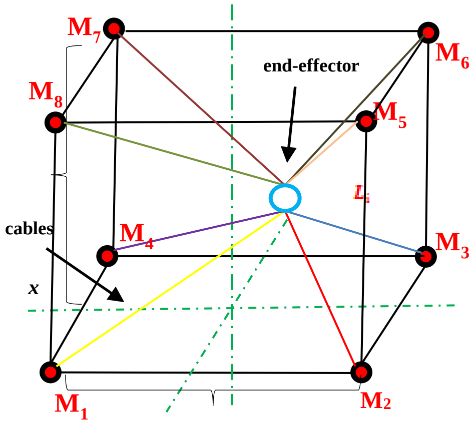


Fig. 2a: The general geometrical parameters

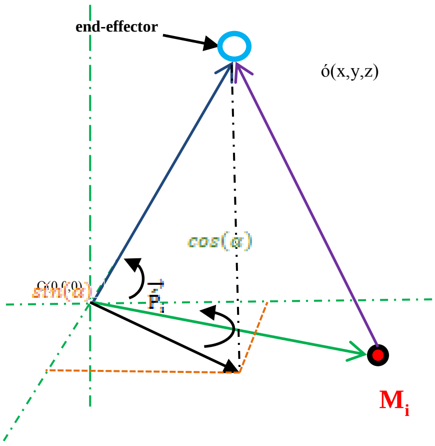


Fig. 2b: The vector analysis that applies to a part of the robot

With:

- LB: The lengths of the side of the workspace (LB = 0.65 m).
- Li (i=1,..4): the lengths of the cables (Li =0.325 m).
- $\overrightarrow{P_1}$: vector to (ò , o);
- $\overrightarrow{S_1}$: vector to (a , M1);
- Li: length of the cable;
- R: side length of the robot base.
- $\overrightarrow{d_1}$: vector to (a, ò).
- H: height between the base and the motor 8;
- Mi: exit point of the cables from the base;
- $\mathcal{R}^*$:Unitary matrix ;
- $\vec{a_i}$: vector to (M1, o);

3 Inverse Geometric Model (IGM)

This section illustrates how to determine the lengths of the cables "Li", the angles "Qi" between the X,Y axes and the cables connected to the platform and "αi" between the Z axis and the planar plane X, Y. The inverse geometric model can be expressed by the following equations, [10].

$$Li = \sqrt{(x - Aix)^2 + (y - Aiy)^2 + (z - Aiz)^2} \; ; \qquad (1)$$

$$\Theta i = \arctan g(\frac{y - Aiy}{x - Aix}) \; ; \qquad (2)$$

$$\alpha i = \arctan g(\frac{z - Aiz}{\sqrt{(x - Aix)^2 + (y - Aiy)^2}}) \; ; \qquad (3)$$

With: i=1…8.

4 Dynamic Model of the End Effector

In order to analyze the input-output behavior of the cable-based robot under consideration, we present the dynamic model, which describes the equation of motion of the end-effector, [11]:

$$M(X)\ddot{X} + N(X, \dot{X}) = \tau \qquad (4)$$

Where:

$$\tau = \begin{bmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \\ \vdots \\ \tau_8 \end{bmatrix} \qquad (5)$$

Is: the vector of the tensions of each cable.
And

$$N(X,\dot{X}) = S(X)(J\frac{d}{dt}\frac{\delta\beta}{\delta X} + C\frac{\delta\beta}{\delta X}\dot{X}) \quad (6)$$

The relationship between the applied forces acting on the end-effector and the cable tensions ti can be expressed as follows:

$$F_R = S * t \quad (7)$$

Where:
FR :represents the external forces acting on the end-effector.
S :is the jacobian matrix.

$$F_R = \left(F_{Rx}\ F_{Ry}\ F_{Rz}\right)^T$$

$$S = \begin{pmatrix} c(\alpha_1)c(\Theta_1) & c(\alpha_2)c(\Theta_2) & c(\alpha_3)c(\Theta_3) & c(\alpha_4)c(\Theta_4) & s(\alpha_5)c(\Theta_5) & s(\alpha_6)c(\Theta_6) & s(\alpha_7)c(\Theta_7) & s(\alpha_8)c(\Theta_8) \\ c(\alpha_1)s(\Theta_1) & c(\alpha_2)s(\Theta_2) & c(\alpha_3)s(\Theta_3) & c(\alpha_1)s(\Theta_1) & s(\alpha_5)s(\Theta_5) & s(\alpha_6)s(\Theta_6) & s(\alpha_7)s(\Theta_7) & s(\alpha_8)s(\Theta_8) \\ s(\alpha_1) & s(\alpha_2) & s(\alpha_3) & s(\alpha_4) & c(\alpha_5) & c(\alpha_6) & c(\alpha_7) & c(\alpha_8) \end{pmatrix} \quad (8)$$

with c(θ) and s(θ) represent cos(θ) and sin(θ) respectively.
We introduce the system states that present the dynamical model in state space form:

- $\dot{x}_{12d}(t) = x_{22d}(t)$
- $M_{11}\dot{x}_{22d}(t) + M_{12}\dot{x}_{42d}(t) + M_{13}\dot{x}_{62d}(t) = u_1(t) - N_{11}x_{22d}(t) - N_{12}x_{42d}(t) - N_{13}x_{62d}(t)$
- $\dot{x}_{32d}(t) = x_{42d}(t)$
- $M_{21}\dot{x}_{22d}(t) + M_{22}\dot{x}_{42d}(t) + M_{23}\dot{x}_{62d}(t) = u_2(t) - N_{21}x_{22d}(t) - N_{22}x_{42d}(t) - N_{23}x_{62d}(t)$
- $\dot{x}_{52d}(t) = x_{62d}(t)$
- $M_{31}\dot{x}_{22d}(t) + M_{32}\dot{x}_{42d}(t) + M_{33}\dot{x}_{62d}(t) = u_3(t) - N_{31}x_{22d}(t) - N_{32}x_{42d}(t) - N_{33}x_{62d}(t)$

(9)

Where:

$$J\ddot{\beta} + C\dot{\beta} = \tau - rt \quad (10)$$

With : ri = r(i=1.2…8).
β :is the rotation angle of the pulley (like in Figure 3).

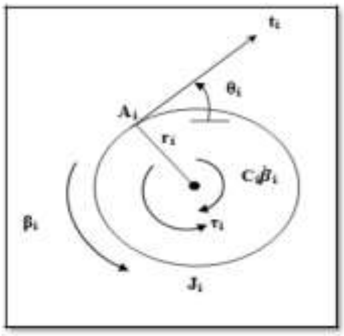


Fig. 3: The structure diagram of the pulley /shaft

From equation 10:

$$t = \frac{1}{r}(\tau - J\ddot{\beta} - C\dot{\beta}) \quad (11)$$

$$\beta = \begin{pmatrix} \beta_1(X) \\ \beta_2(X) \\ \vdots \\ \beta i(X) \end{pmatrix} = \frac{1}{r}\begin{pmatrix} L_{10} - L_1 \\ L_{20} - L_2 \\ \vdots \\ L_{i0} - L_i \end{pmatrix} \quad (12)$$

Ci: The viscous damping coefficients of each motor shaft.
Ji: The inertia of the rotor and the pulley of each motor.
The state space representation can be derived in the general form.

$$X(t) = F(X,t) + g(X,t) * U(t) \quad (13)$$

Where:
$$U(t) = \begin{bmatrix} 0 \\ u_1(t) \\ 0 \\ u_2(t) \\ 0 \\ u_3(t) \end{bmatrix} \quad (14)$$

X(t) represents the state space vector, while F(X, t), g(X, t) are nonlinear functions and U(t) represents the command vector. The resulting tension at the end effector leads it to move towards the required position on its workspace. However, to work properly, an additional constraint should be fulfilled concerning the dynamical equilibrium of the end-effector. This means that, in order to prevent any cable from collapsing, all the cables should be maintained under minimal and positive tensions.

5 Optimization Process

Workspaces are one of the kinematic aspects of parallel robots. All positions accessible to the end-effector enable the construction of the workspace, which may be characterized in most cases by an association of basic geometric models, [12], [13]. The workspace can then be mathematically expressed and incorporated into the expression of an objective function. The aim function can be coupled with and manage an additional kinematic characteristic known as singularities distribution. In this formulation, we address the design challenge of a CUBE cable-based parallel robot for a particular workspace with a minimum tension that is always positive throughout all cables.

Figure 4 shows the proposed approach for rehabilitation exercises in two planes, horizontal and vertical axes, [14]. Furthermore, it consists of three different parts: the genetic algorithm represented by the PID controller, the tension calculation in order always positive and pulley angle β to determine the cable lengths Li.

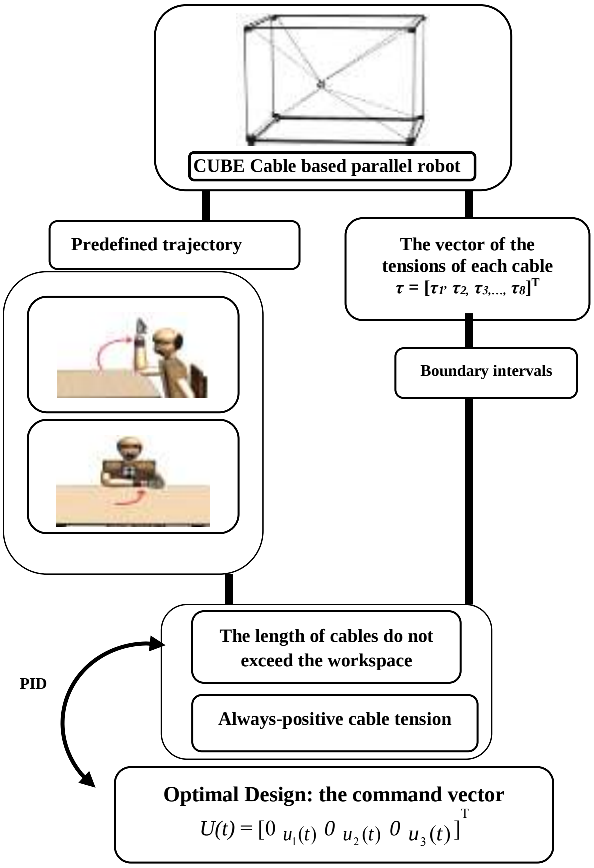
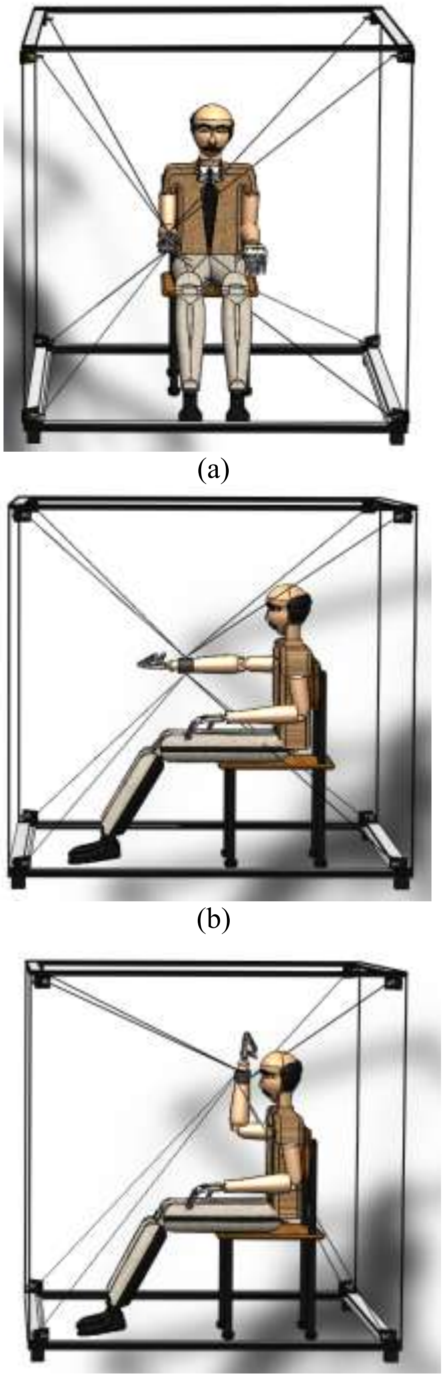


Fig. 4: Optimal design approach for cube- cable based parallel robot for prescribed workspace

6 Simulation Exercises

Based on the geometric concept with solidworks software, shown in Figure 5 (a,b and c) , a first Concept design of the structure has been constructed to produce a prototype. Furthermore displayed is the shortest distance between the cables and the patient during the rehabilitation exercise, [15]. Figure 6 illustrates Flexion of the upper arm in the vertical plane and Figure 7 shows the movement that did by the patient. Figure 8 and Figure 9 present respectively the lengths and the tensions necessary to do rehabilitation tasks in the vertical plane. The same way for the horizontal plane.



(c)

Fig. 5(a.b.c): Criteria for safety in vertical rehabilitation tasks.

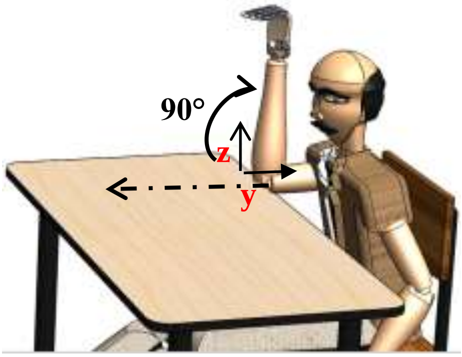


Fig. 6: Flexion of upper arm in vertical plane

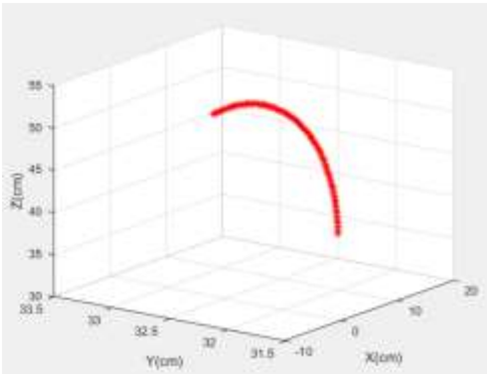


Fig. 7: The movement that did by the patient
In the vertical plane.

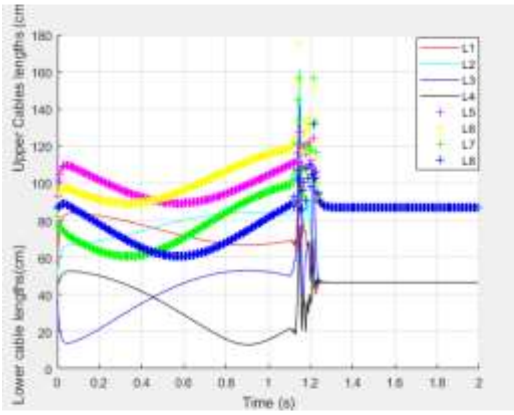


Fig. 8: The lengths necessary to do rehabilitation tasks in vertical plane

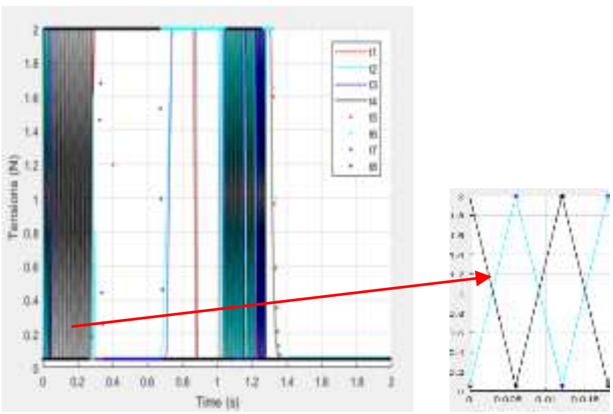


Fig. 9: The tensions necessary to do rehabilitation tasks in vertical plane

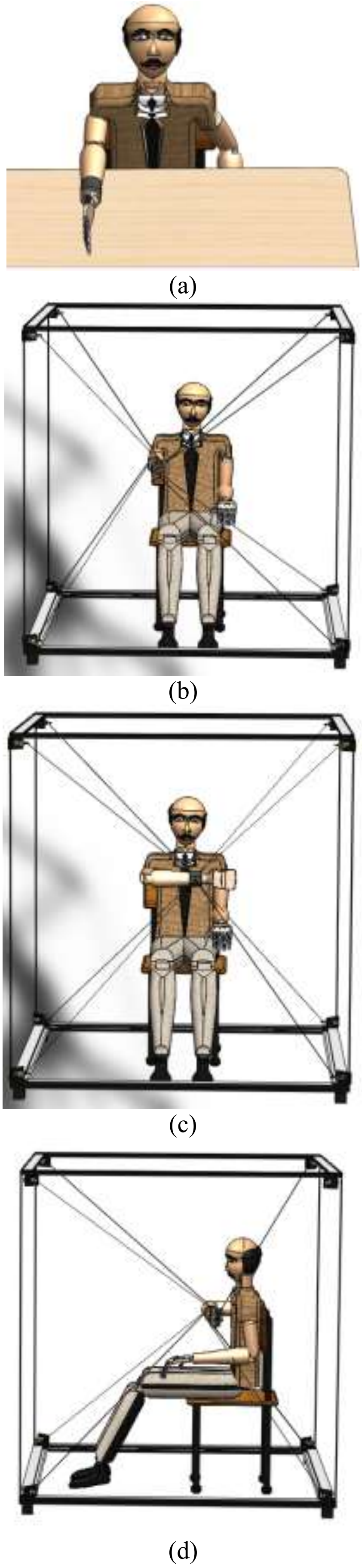


Fig. 10 (a.b.c.d): Criteria for safety in horizental rehabilitation tasks.

Fig. 11: Flexion of upper arm in horizontal plane

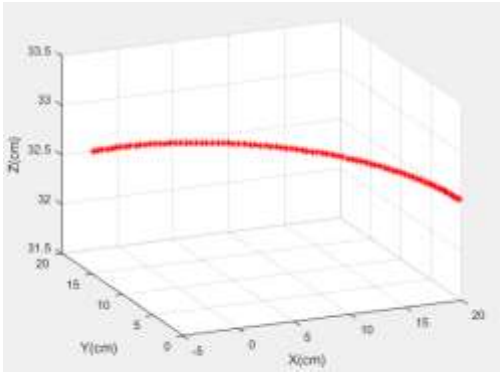


Fig. 12: The movement that did by the patient
In the horizontal plane

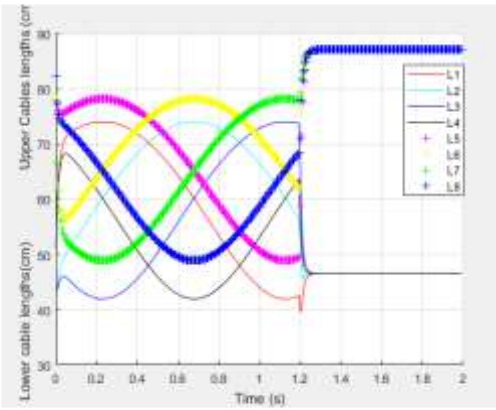


Fig. 13: The lengths necessary to do rehabilitation tasks in horizontal plane

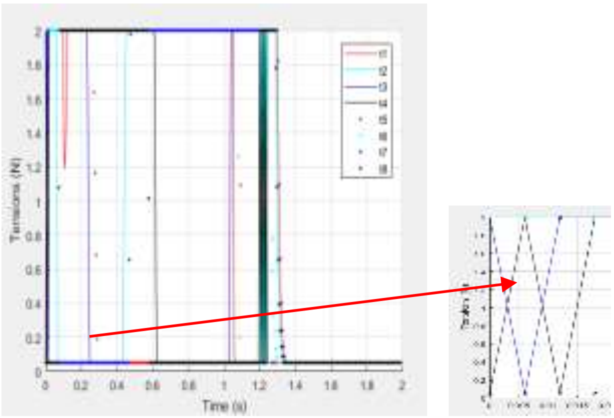


Fig. 14: The tensions necessary to do rehabilitation tasks in horizontal plane

The criteria for safety in horizontal rehabilitation tasks are presented in Figure 10 whereas, the flexion of upper arm in horizontal plane is presented in Figure 11. Similarly, the movement in the horizontal plane of the patient is presented in Figure 12. Lastly, it is worth mentioning that Figure 13 presents the necessary lengths to do rehabilitation tasks in horizontal plane whereas, Figure 14 showcases the tensions necessary to do rehabilitation tasks in horizontal plane.

The simulation rehabilitation activities in horizontal and vertical planes illustrate the best configuration design from the side of the largest workspace, patient safety and the performance of cable movements and the tensions necessary to do rehabilitation movement into both planes. This last, to always maintain the position of the cables in their taut, we are limited to the tensions with t_max (2N) and t_min (0N) in order to always be positive.

7 Conclusion

The topology of a cube, cable-based parallel robot (CBPR) is the topic of this research. This paper exposes CUBE, for cable-based parallel robot for the assistance of patients in rehabilitation exercising. The main movements involved vertical and horizontal planes. In this way, we have taken in account the positive of tensions which are limited with t_min and t_max and also patient motions have been measured in order to identify a safe workspace (the cables do not exceed the work space) required for a rehabilitation. Simulation rehabilitation exercises show the best candidate for rehabilitation exercise purposes such as large workspace, re-configurable architecture, and portability effectiveness.

References:

[1] Marc Gouttefarde & Tobias Bruckmann ‘Cable-Driven Parallel Robots’ Encyclopedia of Robotics pp 1-14, February 2022.

[2] C. Butefisch, H. Hummelsheim, P. Denzler, and K. H. Mauritz, “Repetitive training of isolated movements improves the outcome of motor rehabil-itation of the centrally paretic hand,” J. Neurol. Sci., vol. 130, no. 1, pp. 59–68, 1995.

[3] M. L. Aisen and H. I. Krebs, “The effect of robot-assisted therapy and rehabilitative training on motor recovery following stroke,”

Stroke, vol. 28, pp. 443–446, 1997.
[4] Cafolla, D., Russo, M., & Carbone, G. (2019). CUBE, a Cable-driven Device for Limb Rehabilitation. Journal of Bionic Engineering, 16(3), 492–502.
[5] Major K A, Major Z Z, Carbone G, Pîslă A, Vaida C, Gherman B, Pîslă D L. Ranges of motion as basis for robot-assisted poststroke rehabilitation. Human and Veterinary Medicine, 2016, 8, 192–19.
[6] Sheng B, Meng W, Deng C, Xie S Q. Model based kinematic & dynamic simulation of 6-DOF upper-limb rehabilitation robot. Proceedings of Asia-Pacific Conference on Intelligent Robot Systems (ACIRS), Tokyo, Japan, 2016, 21–25.
[7] Tanev T K, Cammarata A, Marano D, Sinatra R. Elastostatic model of a new hybrid minimally-invasive-surgery robot. The 14th IFToMM World Congress, Taipei, Taiwan, 2015.
[8] Inel. F, M. Khadem, A. Slimane Tich Tich.' Realization and Simulation a Novel Kind of Parallel Cables-Based' WSEAS Transactions on Circuits and Systems, p. 277-284, Vol. 21, 2022, https://doi.org/10.37394/23201.2022.21.30.
[9] Inel. F, Bouchmal, B. and Khochmane, L. "Modeling and control of new model in a spatial coordinates -3D- for cable-based robots", World Journal of Engineering, Vol. 12 No. 2 (2015), pp. 189-200.
[10] Williams, R.L., P. Gallina, and A. Rossi. Planar cable-direct-driven robots, part i: Kinematics and statics. In Proceedings of the 2001 ASME Design Technical Conference, 27th Design Automation Conference. 2001.
[11] Williams II, R.L. Parallel robot projects at ohio university. In Workshop on fundamental issues and future research directions for parallel mechanisms and manipulators, Quebec City, Canada. 2002.
[12] Loureiro R, Amirabdollahian F, Topping M, Driessen B, Harwin W. Upper limb robot mediated stroke therapy — GENTLE/s approach. Autonomous Robots, 2003 15, 35–51.
[13] Lamine H, Laribi M A, Bennour S, Romdhane L, Zeghloul S. Design study of a cable-based gait training machine. Journal of Bionic Engineering, 2017, 14, 232–244.
[14] Pusey J, Fattah A, Agrawal S, Messina E, Jacoff A. Design and workspace analysis of a 6–6 cable-suspended parallel robot. Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems, Las Vegas, USA, 2003.
[15] Laribi, M. A., Carbone, G., & Zeghloul, S. (2019). On the Optimal Design of Cable Driven Parallel Robot with a Prescribed Workspace for Upper Limb Rehabilitation Tasks. Journal of Bionic Engineering, 16(3), 503–513.

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

- Foued Inel: Conceptualization, prototyping and testing
- Mohammed Khadem: methodology, prototyping and testing, supervision
- Abdelghafour Slimane Tich Tich: testing, supervision.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

No funding was received for conducting this study.

Conflict of Interest

The authors have no conflict of interest to declare.