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CABLE-DRIVEN ROBOTS FOR CIRCULAR TRAJECTORY EXERCISES IN REHABILITATION

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Abstract. *Motor functions of stroke patients are frequently related and evaluated using circle drawing/tracing tasks as studies showed that stroke patients drawing a circle produce elliptical shapes instead of round. In this way, this paper presents the design of three cable-driven robots that can be used in circular trajectory rehabilitation of upper limb. First, a planar circular trajectory and the mathematical model to reach this desired trajectory and to maintain cables in tension are presented. After, a serious game for the circular trajectory to stroke rehabilitation is described. The experimental results show a satisfactory behavior reproducing the circular curve while is expected to produce a comfortable motion to the patient during the rehabilitation therapies. The next step is to implement a circular trajectory with the cable-driven robots in the rehabilitation of stroke patients.*

Keywords: *robotics, cable-driven, circular trajectory, rehabilitation, stroke.*

1. INTRODUCTION

Stroke is the leading cause of disability and leaves a significant number of individuals with motor and cognitive deficits. The paralysis of the upper limb is the most frequent consequence of brain injury (Tappeiner et al., 2018).

Rehabilitation training is the most effective way to reduce motor impairments in stroke patients and robots can be suited for this purpose since they can train patients for long durations with precision (Hatem et al., 2016). Different types of robot are being studied to rehabilitation like industrial robots, exoskeletons, and cable-driven robots.

Industrial robots, often used for rehabilitation, usually have rigid structures, are fast, and several safety issues must be considered when applying them to rehabilitation (Mao et al., 2015). Exoskeletons for rehabilitation face a huge variability of human limbs shape and dimensions, making it difficult to match the human and robot joints rotation centers (Beyl et al., 2009).

The cable-driven robots consist of an end-effector, linked by one or more cables (variable lengths) to a fixed platform. The end-effector move by changing the cables lengths while preventing them to became slack. These robots have characteristics that can make them suitable for rehabilitation purposes such as large workspace, transportability, flexibility, reconfigurability, low weight/inertia and can makes the patient feel less constrained (Alves et al., 2018; Gonçalves et al., 2015; Gonçalves and Carvalho, 2014).

Thus, cable-driven robots can be an efficient way of increasing the intensity of stroke rehabilitation (longer and more frequent training) in rehabilitation clinics, hospital bed or even patient's home (Schmidt, 2018).

Moreover, these systems can be coupled with virtual reality simulators, enhancing conventional physical therapy since they can record patient information (exercise time, the speed of movement, peak, and average velocities, etc.), providing an objective measure of the progress and outcomes of therapy (Ceccarelli et al., 2010).

These measures can offer a sensitive, accurate and time-efficient approach for the assessment of sensorimotor function after neurological impairment compared to standard clinical assessments. Besides that, motor functions of stroke patients are frequently related and evaluated using circle drawing/tracing tasks (Dipietro et al., 2007; Hussain et al., 2017).

Previous studies showed that abnormal coupling of shoulder and elbow influences circle drawing performance, and, instead of round shapes, elliptical shapes are produced by stroke patients drawing a circle. The training can increase the hemiparetic arm work area in stroke patients and circle drawing performance (Krabben et al., 2012), even when subjects do not train for circle drawing, only for point-to-point movements (Krebs et al., 2009), that demonstrates skill learning in joint movements coordination.

The InMotion ARM^{TM}, the commercial version of MIT-MANUS, is a robotic arm with two active degrees of freedom (DOF). It is the most researched device for upper limb rehabilitation (tested in over 1000 patients) and also uses a circle evaluation test to measure the range of motor coordination, joint independence, and coordinated movement planning. Evaluation for stroke patients at admission and discharge following robotic therapy with this device shows improvements in circle drawing pattern (Dipietro et al, 2007, InMotion, 2019).

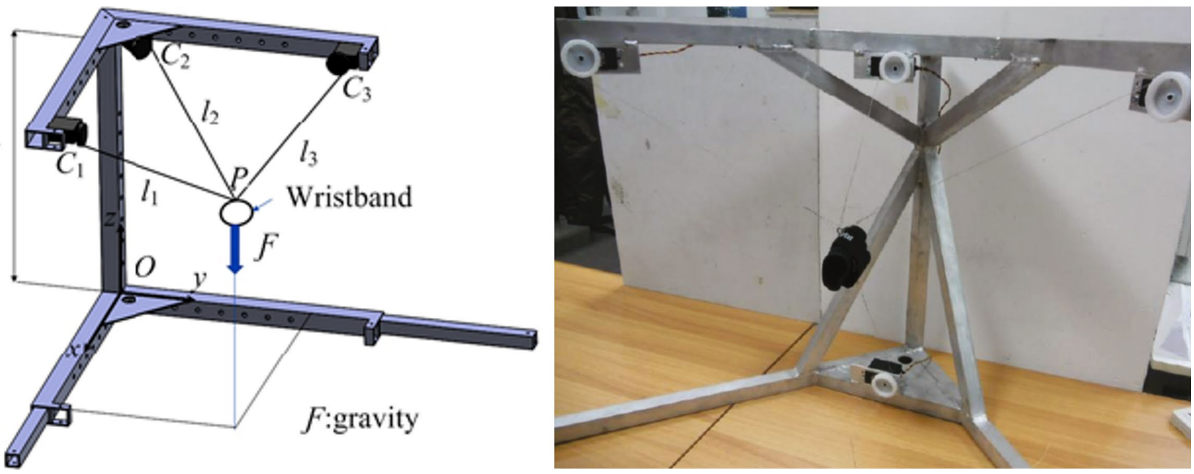
Thus, in this paper are presented different cable-driven robots to be applied in stroke rehabilitation focusing in the circular trajectories. First, the Lawex, the CUBE and the CAR Cable-Driven robot prototypes are introduced. After, the mathematical model of circular trajectory applied to these structures is presented followed by the description of serious game developed. Finally, the experimental tests show that these structures are suitable to be applied in rehabilitation procedures using circular trajectories.

2. DESIGN OF CABLE-DRIVEN ROBOTS

As mentioned, cable-driven robots can be a good solution for an inherently safe device since their links have very low inertial forces and cables can be designed to break at the desired tension force. Additionally, these devices can meet the requirements for safety, comfort, ease of manipulation and portability (Ceccarelli and Romdhane, 2010; Carbone and Ceccarelli, 2016).

2.1 Design of the Limb Wire Driven Exercising device (Lawex)

A cable-driven robot solution named Lawex (Carbone et al., 2017; Laribi et al., 2019) is presented in this paper. In cable-driven robots, cable lengths are adjustable in order to control the end effector's position and orientation. This makes it easier to adapt to the different human limb sizes, allowing a much wider array of patients use. Based on exercises type and complexity, cables can be either added or removed. However, the more cables are introduced into the structure, the more complex and expansive it becomes. Accordingly, this proposed device, Fig. 1, has four cables, allowing three degrees of freedom.



(a) (b)

Figure 1. The cable driven robot Lawex and a wristband as its end-effector: (a) CAD model (Laribi et al., 2019); (b) built prototype (Carbone et al., 2017)

Figure 2 shows a boundary of the accessible workspace that represents all reachable positions for the platform but not necessary for satisfying the condition of only-pulling on cables. The rehabilitation exercise was studied in order to identify the prescribed workspace for this device, which the rehabilitation task is focused on the upper limb motion. The human forehand range of motion is covered by the robot workspace, proving that the robot is capable of the forearm rehabilitation task and particularly to reproduce semicircular trajectories.

A condition of positive tensions should be satisfied at all poses of the mobile platform of a cable driven robot. Thus, the identification of the accessible workspace is not enough to perform the design issue. In the Lawex robot, the maximum achievable workspace is a trigonal prism. The three motors constitute the upper vertices of this prism, as shown in Fig. 3. The prescribed workspace must be inside this static equilibrium workspace.

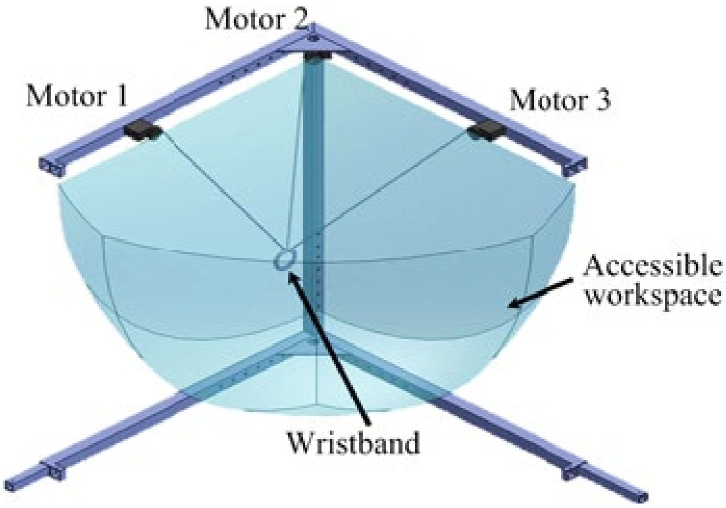


Figure 2. Tridimensional representation of Lawex accessible workspace (Laribi et al., 2019).

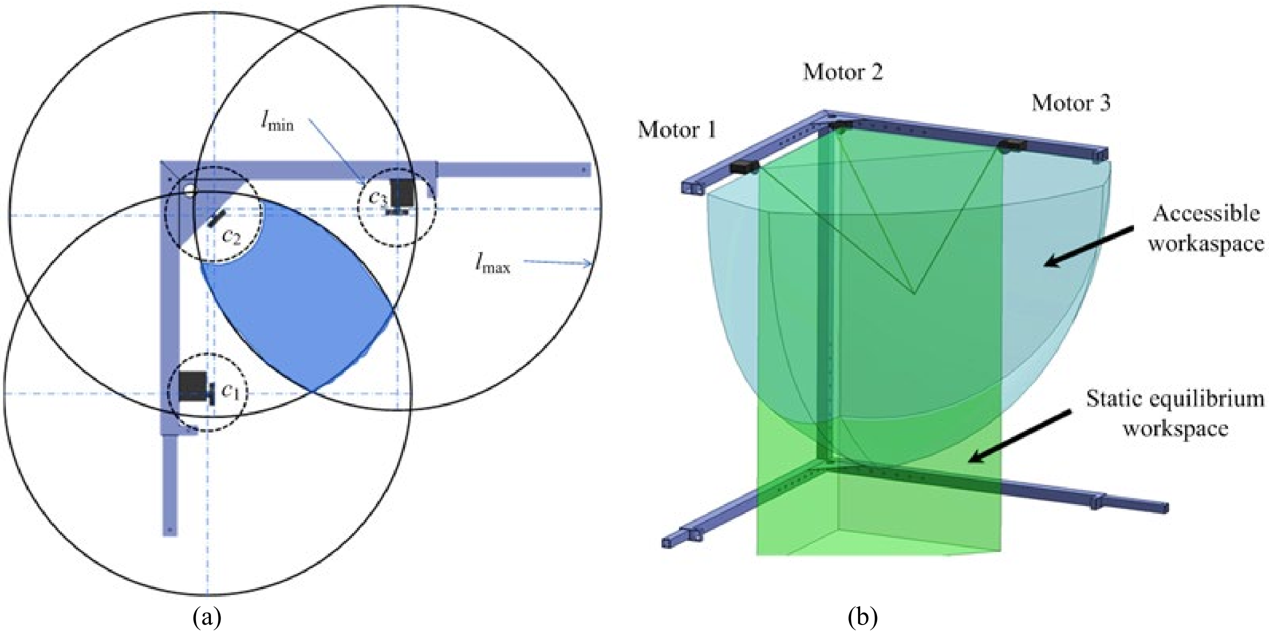


Figure 3. (a) Accessible workspace slice in XY plane; (b) static equilibrium workspace for a three-cable (Laribi et al., 2019)

Four 24 V DC motors with encoder are used in the prototype. These actuators have a 1:150 reduction ratio, achieving a torque of 1.5 Nm. Each motor receives a speed input that depends on the current (acquired by the encoder) and the desired position difference. While the actuator is moving, the speed decreases until the desired position is reached.

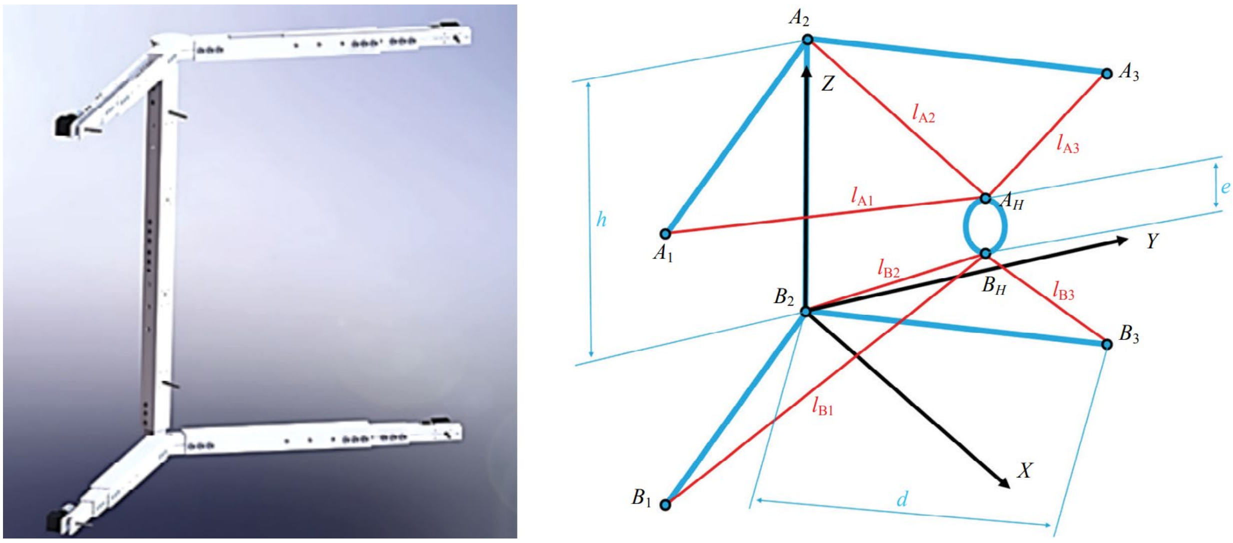
A dual H-Bridge motor driver module, L298N, has been chosen to control both the rotation sense and the speed. This motor driver allows speed and direction control of two DC motors. The control is performed by an Arduino MEGA that sends the sense of rotation and the desired speed using PWM to the motor drivers to reach the desired position. The synchronization of the four motors is fundamental to maintain the cables in tension and allow the system to work properly.

If one neglects the cables elasticity, each cable length can be considered as directly proportional to the angular displacement. As each winch consists of a cylindrical drum of known diameter, each servomotor rotation generates a known increase/decrease of the cable length. There is a developed interface to Lawex programming that runs in Java and can also be operated with Android smartphones. One can set trajectories by setting up a list of the point coordinates one wishes to reach versus time (Boschetti et al., 2019).

2.2 Cable-driven device for Upper and lower limB Exercising (CUBE)

The proposed design for CUBE (Cafolla et al., 2019), Fig. 4, is a 5 DOF parallel manipulator with a cable-driven architecture based on six cables for rehabilitation of both upper and lower limbs. The kinematics of the device is characterized by a fixed frame with adaptable geometry. The end-effector is ring-shaped and is worn by the user as a wristband. Its position is controlled by the six cables (end-effector with 3 DOF in position) while its orientation is assumed to be constrained by fixed support for the elbow on the Z-axis and fixed on the X and Y-axis.

Three cables are attached to the upper part of the structure in points A_1, A_2, and A_3, and they converge into point A_H of the end-effector, Fig. 4 (b). The remaining three cables are attached to the lower part of the structure in points B_1, B_2, and B_3, and they converge into point B_H of the end-effector, Fig. 4 (b).



(a) (b)

Figure 4. CUBE: (a) CAD design of the first prototype; (b) kinematic scheme (Cafolla et al., 2019)

Six 24 V DC motors with encoder are used. The characteristics, operation and control of these actuators are the same as mentioned for Lawex.

Figure 5 shows the reachable workspace of the CUBE latest design, which is adequate for the motion range of rehabilitation exercises and can contain a circular trajectory inside it.

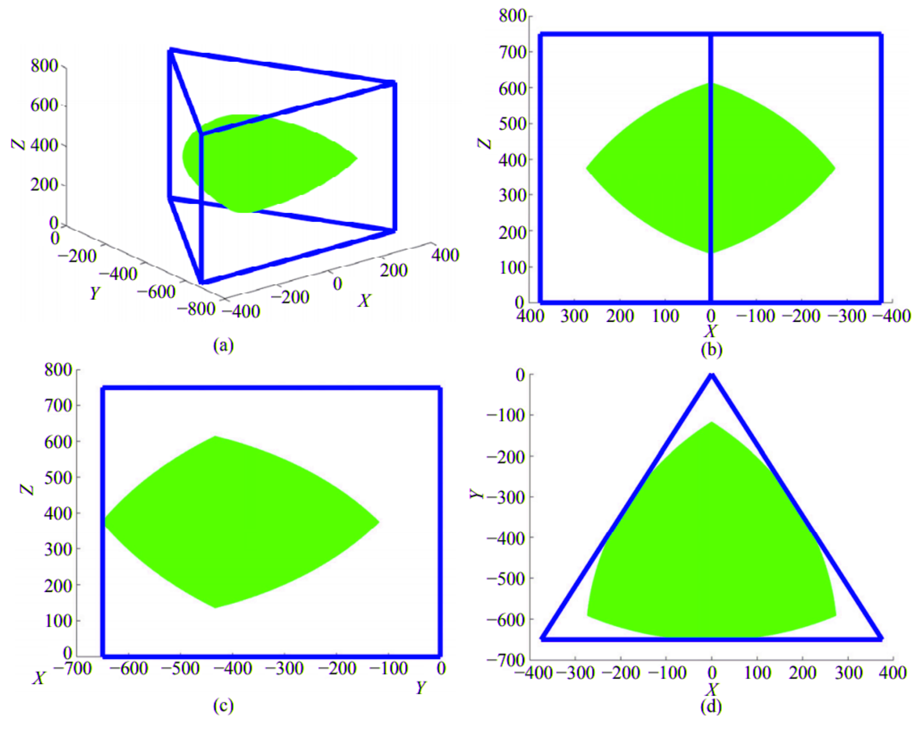


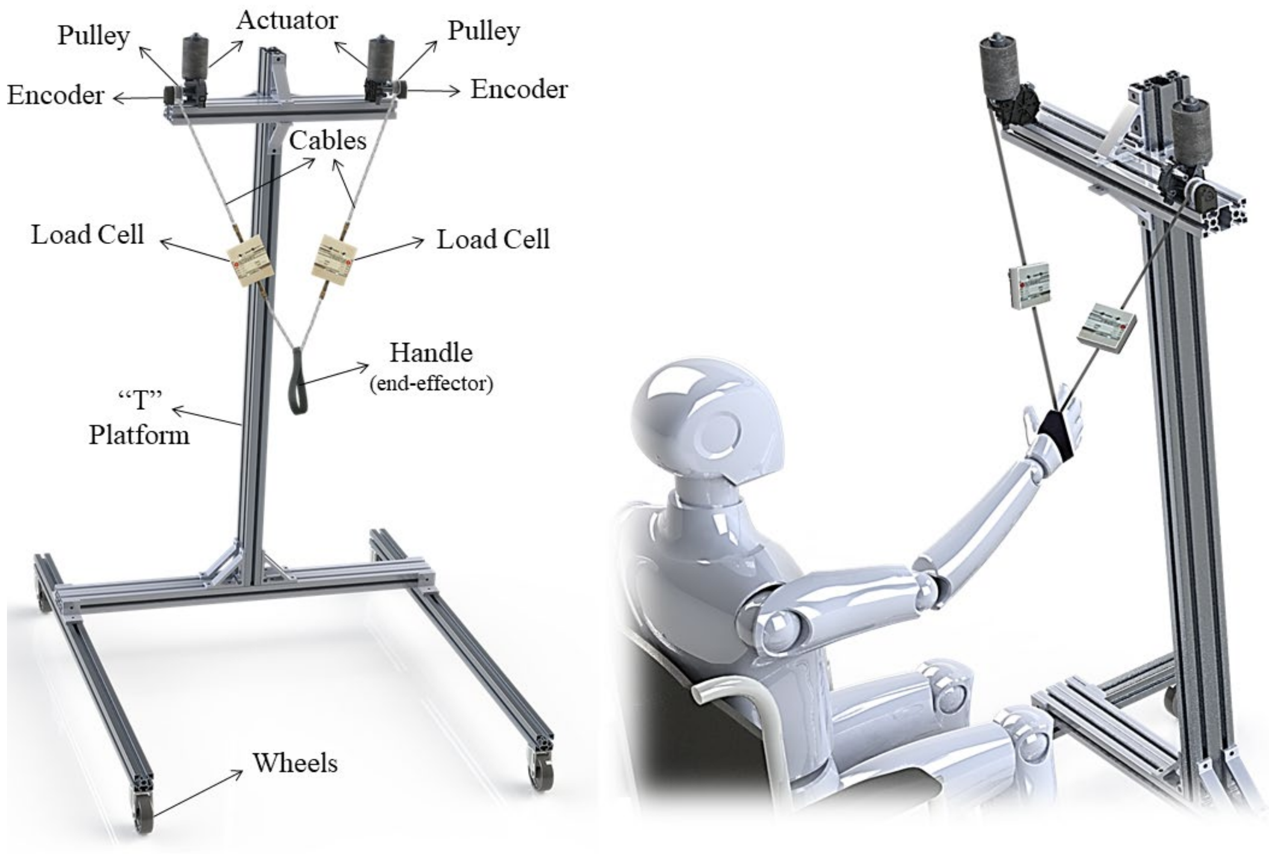
Figure 5. Workspace of CUBE. (a) Isometric view; (b) front view; (c) lateral view; (d) top view (Cafolla et al., 2019)

2.3 Design of the Cable-Driven Robot CAR

The Cable-Actuated Robot (CAR), developed at LAR/UFU, is a 2 DOF cable-driven robotic structure with an end-effector, handle/strap, Fig. 6. The structure consists of an aluminum fixed frame, DC motors, load cells, and rotary encoders.

The motors are powered by 24 V DC voltage, the nominal torque and power are respectively 10 Nm (48 Nm peak) with rotational speed up to 45 RPM. Each load cell has a 20 kgf capacity and the resolution of the measuring system is 0.025 kgf. The encoders are incremental and produce 500 ppr (pulses per revolution).

The control is a position proportional and it is performed by an Arduino MEGA with MATLAB (through Arduino Hardware Support Package to enable communication) and a full bridge motor driver VNH2SP30 (up to 2 actuators and 30 A). The actuators speed input depends on the current and the desired position difference and, while moving, the speed decreases until the desired position is reached. The Arduino MEGA sends the sense of rotation and the desired speed using PWM to the motor driver to reach the desired position.



(a) (b)

Figure 6. Cable-driven device: (a) CAD design of the prototype; (b) prototype in use (simulation).

The video of this proposed device can be accessed on https://goo.gl/WwtYg4. The results of the validation performed with this device showed high accuracy and repeatability levels (Alves et al, 2019).

3. CIRCULAR TRAJECTORY MODEL FOR CABLE-DRIVEN ROBOT

The circular trajectory was chosen because it is common to use circle evaluation tests to measure the motor coordination and joint independence in stroke patients. These patients produce elliptical shapes, instead of round, when drawing a circle; after rehabilitation training their performance in this task can increase. In addition, this trajectory has a regular and symmetrical shape, making it easier to recognize any path deviation, even visually.

In the structures presented in section 2, the cables are interlinked through the end-effector, generating coupling between the degrees of freedom that enable planar trajectories. The disadvantage of using cables is that they can pull the end-effector, but not push it. In under-constrained cable-driven robots the gravity may be considered in downward movements and to maintain all cables in tension (Gonçalves et al., 2015).

The mathematical modeling to obtain the circular trajectory is performed according to the CAR structure and the same procedure can be applied to Lawex and CUBE structures.

Thus, the cables lengths must be calculated to reach the desired end-effector position $\boldsymbol{P}$ (x_p, y_p, z_p). To generate a planar trajectory either x_p, y_p or z_p must be constant during the movement. Defining z_p as a constant c the desired position become $\boldsymbol{P}$ (x_p, y_p, c) or $\boldsymbol{P}$ (x_p, y_p). As the cables must always be in tension, they are considered as rigid links in the model, and thus two cables will form a triangle with the fixed base and end-effector as shown in Fig. 7 (a).

The mathematical model can be written from Fig. 7 (b), where the cable lengths are represented by L_1 and L_2, and $\boldsymbol{A}/\boldsymbol{B}$ and $\boldsymbol{P}$ (desired position) are the points where the cable L_1/L_2 are attached in the base and the mobile platform, respectively; the distance between point $\boldsymbol{A}$ and $\boldsymbol{B}$ is given by W_b.

For an example of circular trajectory where the motion amplitude is a (diameter) and the center of the trajectory in C (x_c, y_c), the desired position $\boldsymbol{P}$ (x_p, y_p) is given by Eq. (1) and Eq. (2), respectively:

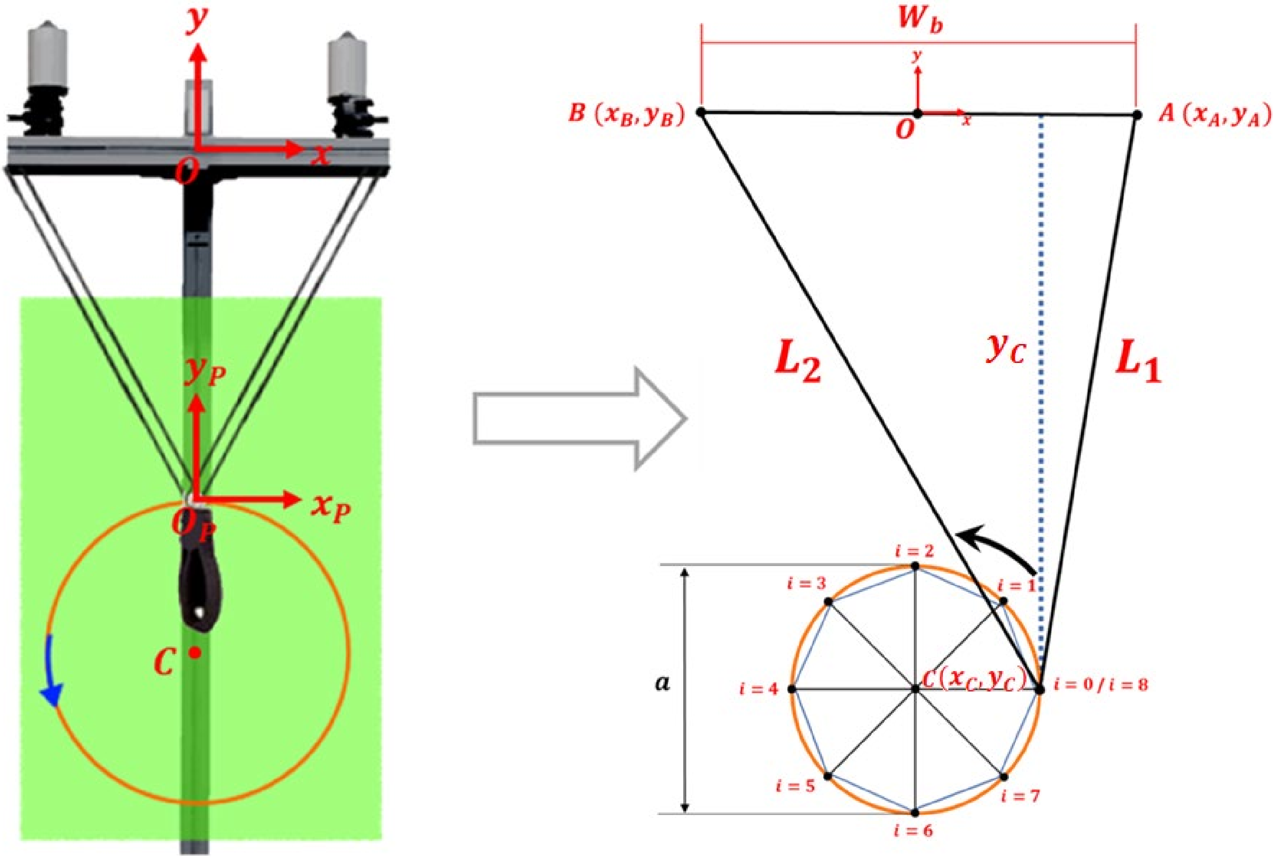
$$x_p = x_c + \frac{a}{2}\cos\theta \tag{1}$$

$$y_p = y_c + \frac{a}{2}\sin\theta \tag{2}$$

Where θ is the angle inside the circular trajectory and can be discretized as follows:

$$\theta = i \times \frac{2\pi}{N}, \qquad for\ i = 0,1,2,\ldots,N \tag{3}$$

Where N is the number of discretization points and i is the index. A spline can be used to interpolate the points and produce smoother movement.



(a) (b)

Figure 7. Circular Trajectory: (a) computational model showing the planar workspace (green region) and a possible circular trajectory; (b) schematic simplification to obtain the mathematical model.

Thus, the cable lengths are calculated using Eq. (4) and Eq. (5):

$$L_1 = \frac{y_C + \frac{a}{2} sin\left(i \times \frac{2\pi}{N}\right)}{sin\left(tan^{-1}\frac{\left(y_C + \frac{a}{2} sin\left(i \times \frac{2\pi}{N}\right)\right)}{\left(x_C + \frac{a}{2} cos\left(i \times \frac{2\pi}{N}\right)\right) - \frac{W_b}{2}}\right)} \quad (4)$$

$$L_2 = \frac{y_C + \frac{a}{2} sin\left(i \times \frac{2\pi}{N}\right)}{sin\left(tan^{-1}\frac{\left(y_C + \frac{a}{2} sin\left(i \times \frac{2\pi}{N}\right)\right)}{\left(x_C + \frac{a}{2} cos\left(i \times \frac{2\pi}{N}\right)\right) + \frac{W_b}{2}}\right)} \quad (5)$$

For polygonal trajectories such as triangles, quadrilaterals, and pentagons, it is enough to decrease the number of discretization points to 3, 4 and 5 respectively. The video with the proposed trajectories (circular and polygonal trajectories) can be accessed on https://goo.gl/ZM4g2Q.

If necessary, a rotational angle α can be added in Eq. (3) to rotate the polygon. This angle is shown in Eq. (6):

$$\theta = i \times \frac{2\pi}{N} + \alpha, \qquad for\ i = 0,1,2,\ldots,N \quad (6)$$

4. SERIOUS GAME TO CIRCULAR TRAJECTORY REHABILITATION

Serious games for stroke rehabilitation are being developed with these devices. Among the developed games, the RoundPizza, Fig. 8, follows motion control/virtual reality game style and was developed in Unity together with MATLAB. This game aims to simulate the task of cutting dough in a round pizza shape.

The input movement can be a circular trajectory, applied by the user or the device itself (if the patient cannot voluntarily make the movement), in either, the circular trajectory must follow the plane defined in Fig. 7.

Each game session ends after a predetermined time or the full circle completion. The pizza diameter is related to the amplitude of the exercises.

The roundness can be used to evaluate the circle drawing performance based in specific control points (see next session). The circle drawing performance can demonstrate skill learning in joint movements coordination, as mentioned before. A video with this game can be accessed on https://goo.gl/pnNLU2.

Figure 8. RoundPizza game main screen.

5. RESULTS

Preliminary tests performed with the CAR device reproducing a circular trajectory achieved satisfactory results. A particular test performed with 20 discretization points and radius of 15 cm is shown in Fig. 9 (a). The discretization points are represented in red and the reproduced trajectories in green. This trajectory was repeated six times and the maximum error, related to the control points, Fig. 9 (b), was 1.5654 cm (10.44 %), but in average was 0,3489±0,2746 cm which corresponds to 2,33±1,83%, indicating a good accuracy.

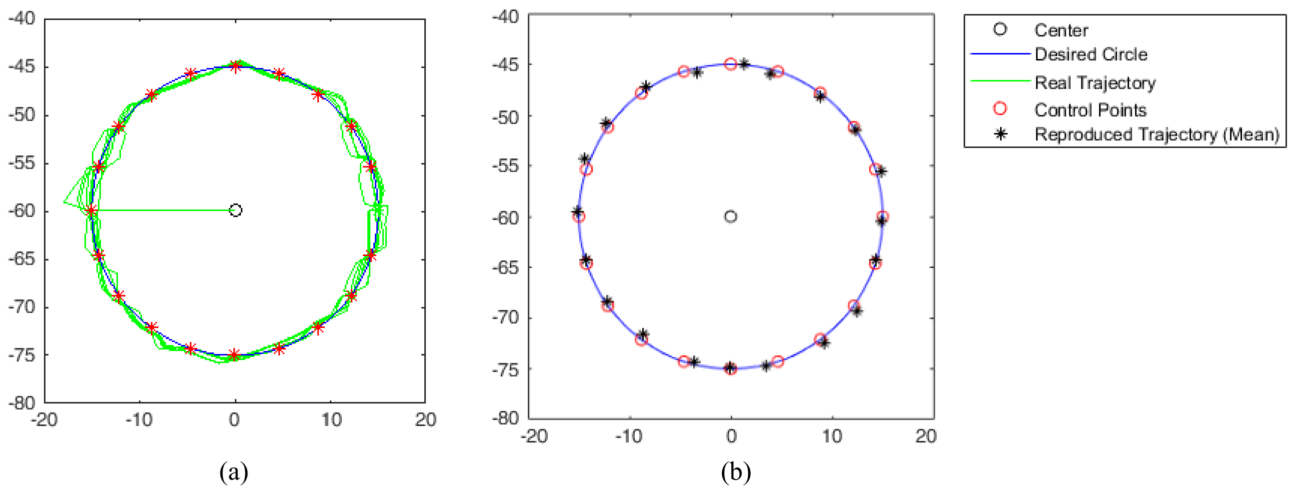


Figure 9. Example of a circular trajectory of 15 cm radius with 20 discretization points: (a) full path (b) control points comparison.

6. CONCLUSION

This paper presents the design of three cable-driven robots that can be used in circular trajectory rehabilitation of the upper limb. A planar circular trajectory model was presented which the angle inside the trajectory are discretized. The mathematical model to reach the desired trajectory and to maintain cables in tension are presented.

The workspace graphical simulations show a satisfactory behavior reproducing the expected curve while is expected to produce a comfortable motion to the patient during the rehabilitation therapies. In this way, the circular trajectory can be taught to the device.

A serious game for the circular trajectory to stroke rehabilitation is described. In this game, the roundness can be used to evaluate the circle drawing performance and, consequently, motor function.

A preliminary test performed with the CAR device with 20 discretization points and radius of 15 cm achieved an average error, related to control points, of 0.3489 cm (2.33 %) indicating a good accuracy.

The next step is to implement a circular trajectory with the cable-driven robots in the rehabilitation of stroke patients.

7. ACKNOWLEDGEMENTS

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