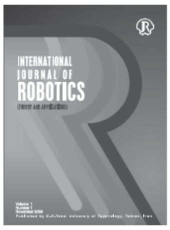

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Model-Free Joint Space Controller for Fully-Constrained Cable-Driven Parallel Robots: a Bio-Inspired Algorithm

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ABSTRACT

Due to the complex model of cables, non-linearity, and uncertainties that exist in Cable-Driven Parallel Robots (CDPRs), this paper proposes a bio-inspired intelligent approach to overcome these challenges. This method, Brain Emotional Learning (BEL), mimics the emotional aspect of the mammal brain. Because of its easy-to-implement mathematical model, the Brain Emotional Learning-Based Intelligent Controller (BELBIC) brings fast adaptation, robustness, and low computational cost. The core idea of this paper is to define new saturated learning functions that eliminate the necessity of calculating the Jacobian matrix and forward kinematics in the control loop while still ensuring positive tensions. To evaluate the effectiveness of the proposed method, an experimental study was conducted using a plotter CDPR. The experimental results indicate that BELBIC can be adopted as a new approach in the trajectory tracking problem in the context of CDPRs, as it provides an acceptable tracking error (less than 10 degrees) without using the Jacobian matrix in the feedback loop.

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1. Introduction

Cable-Driven Parallel Robots (CDPRs) have shown excellent efficiency when performing tasks that require a wide workspace. In addition to their wide working area, fast motion, and ease of assembly, these robots gain many specific advantages by using cables rather than rigid links. One of the most well-known applications, the cable camera system, also known as the spider-cam is used as an aerial robotic system for videography [1]. Another example is the flight simulator based on CDPR, which can produce high accelerations for agile maneuvers [2]. Furthermore, other applications could be found as the cable-driven mobile robot for construction [3], rehabilitation cable robot [4], as well as a variety of other uses [[5]–[7]. Even though cables offer a large working area and numerous advantages, they are only capable of delivering tensile force. Therefore, the need to ensure positive tension causes a significant challenge for control design [8]. Thus, common control principles developed for traditional types of robots cannot be utilized and must be altered.

Motion control of CDPRs can be categorized into two types: cable length coordinates (joint space) and task space. From the practical perspective, task space controllers are costly to implement because of the complicated hardware required for measuring the pose of the moving platform with precision; in contrast, joint space controllers can be built for a significantly lower price as well as it is more straightforward and easier to put into practice. Due to elastic properties, if encoders are used to measure cable length, the pose of a moving platform may not be determined accurately. As mentioned previously, cables can only support tensile forces due to their inherent characteristics. For ensuring positive tension on all cables, the Jacobian matrix's null space is used to calculate a natural internal force that causes no movement in the moving platform but provides positive tension and increases the stiffness [9]. To determine the Jacobian matrix, it is evident that the pose of moving platform must be computed or measured [10].

Nature has always been a factor in shaping human ideas, including control engineering. One of these approaches is called Brain Emotional Learning (BEL), a method derived from the Limbic system. This algorithm which uses the learning process in the Amygdala and the Orbitofrontal cortex (OFC), entitled Brain Emotional Learning, was first proposed in [11], [12]. After a while, this model was used as a model-free control approach, namely Brain Emotional Learning Based Intelligent Controller (BELBIC) and introduced in [13].

As far as BELBIC's advantages are concerned, it has been applied to several domains: pitch control of wind turbines [14], multi-agent systems [15], launch vehicle control [16], attitude control of a quadrotor [17], and electro-hydraulic servo system [18]. Based on the benefits of this algorithm, it was chosen for further development and evaluation using a fully-constrained CDPR. Although the Jacobian matrix and the underlying kinematic parameters must still be known to overcome kinematic uncertainty, Cheah et al. proposed a method of estimating these parameters using approximate Jacobian control laws [19]. A key contribution of this paper is the formulation of a model-free control method that can be applied without the Jacobian matrix, forward kinematics, and measurement of the end-effector pose. By defining learning functions correctly, this will be accomplished. Hence, joint angles yield cable lengths as the only feedback measurement necessary. For experimental verification of the effectiveness of the proposed controller, a fully-constrained robot has been chosen.

Following is an outline of the paper. Section 2 of the paper presents the kinematics and dynamics model for the CDPR. Section 3 outlines the BELBIC algorithm and defines rewards and sensory inputs functions. Section 4 is devoted to the description of the case study and experimental results, with the concluding remarks appearing in section 5.

2. Kinematics and Dynamics

CDPRs consist of a rigid base, guiding pulleys, motors, cables, and an end-effector. Orientation and movement of the end-effector is controlled by the cable lengths variation [20]. A fully-constrained cable robot, the Kamal-ol-molk plotter robot from the ARAS group, represents a case study for the implementation of our proposed algorithm. This robot is equipped with four parallelogram cables driven by three AC motors, and it has a unique end-effector design [21]. The design features of the CDPR result in a redundant planar structure, indicated in Figure 1.

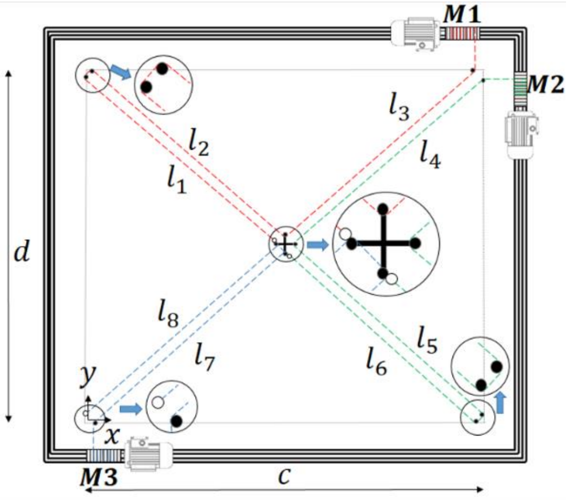


Figure 1. Kamal-ol-molk robot schematic diagram.

Utilizing parallelogram links can help us increase the stiffness of the robot by applying redundant forces on its moving platform. Based on Figure 1, (A_i) indicates the base's fixed anchor points, (B_i) refers to the end effector's movable pulleys, and (l_i) represents cable lengths. Due to the parallelogram links and the moving platform configuration, there are two degrees of freedom transitional to the fixed frame $x = [x_p, y_p]$. Thus, the moving platform orientation remains unaltered. Furthermore, robot length variables can also be defined as $l = [l_1 + l_2 + l_3, l_4 + l_5 + l_6, l_7 + l_8]^T$. It is necessary to define two coordinate systems to derive the mathematical model. To drive the kinematics and dynamics equation of a CDPR, it is needed to define a fixed and a body frame. The first one is attached to the base and defined by the O_f and $x - y$, which are its origin and axes, respectively. The second one is on the end-effector. The inverse kinematics can be driven using the l_j, which can be calculated by p using the loop closure approach. In other words, it indicates the length and orientation of cables:

$$l_j = a_j - p - Rb_j, \tag{1}$$

Where $\boldsymbol{a}_j$ and $\boldsymbol{b}_j$ represent the position of the anchor points located on the base and moving platform, in that order. The following unit vector can be used to describe the orientation of the parallel cables:

$$\boldsymbol{u}_j = \frac{\boldsymbol{l}_j}{\|\boldsymbol{l}_j\|}. \tag{2}$$

Without taking into consideration cable elasticity, it may be assumed that cable length depends on joint angles by the following:

$$\theta_j = r_D l_j. \tag{3}$$

As shown below, r_D represents the radius of the pulleys. Besides, the Jacobian matrix of the case as mentioned above can be driven as follows [21]:

$$\boldsymbol{J}(\boldsymbol{x}) = \begin{bmatrix} \frac{x - x_{A_1}}{l_1} + \frac{x - x_{A_2}}{l_2} + \frac{x - x_{A_3}}{l_3} & \frac{y - y_{A_1}}{l_1} + \frac{y - y_{A_2}}{l_2} + \frac{y - yA_3}{l_3} \\ \frac{x - x_{A_4}}{l_4} + \frac{x - x_{A_5}}{l_5} + \frac{x - x_{A_6}}{l_6} & \frac{y - yA_4}{l_4} + \frac{y - y_{A_5}}{l_5} + \frac{y - y_{A_6}}{l_6} \\ \frac{x - x_{A_7}}{l_7} + \frac{x - x_{A_8}}{l_8} & \frac{y - y_{A_7}}{l_7} + \frac{y - y_{A_8}}{l_8} \end{bmatrix}_{3\times2}. \tag{4}$$

Using the following formula, it is possible to drive the equation motion of the moving platform without considering the elastic and damping characteristics of the cables:

$$\boldsymbol{M}\ddot{\boldsymbol{x}} + \boldsymbol{g} = -\boldsymbol{J}^T\boldsymbol{\tau}, \tag{5}$$

in which,

$$\boldsymbol{M} = \begin{bmatrix} m & 0 \\ 0 & m \end{bmatrix}, \boldsymbol{\tau} = [f_1, f_2, f_3] \tag{6}$$

Where m, $\boldsymbol{g}$, and f_i represent the mass of the moving platform, gravity, and the tension of the cables. Moreover, based on the Newton-Euler equations, the actuator's dynamics can be expressed as follows:

$$\boldsymbol{I}_{\text{total}}\,\ddot{\boldsymbol{\theta}} + \boldsymbol{c}\dot{\boldsymbol{\theta}} + r_D\boldsymbol{\tau} = \boldsymbol{u}, \tag{7}$$

Where $\boldsymbol{I}_{\text{total}}$, $\boldsymbol{c}, \boldsymbol{u}$, and r_D represent the moment of inertia of the motors, damping parameters, the control signal, and radius of the drum, respectively. There is a need to mention that the mathematical equations are true only when there is positive tension on the cable, i.e., $\boldsymbol{\tau} > \boldsymbol{0}$. Unless this tension exists, the robot will not be practical. In section 4, a detailed description of the robot's physical and geometric properties is presented.

3. BELBIC

As part of the design of artificial systems, mathematical models have been conducted to model emotions. Their influence over decision-making was considered unpredictable in the past. However, today, emotions play an increasingly key role in intelligent systems, and they can also influence decisions [13], [22]. The computational model of BEL was proposed by Morén and Balkenius. Due to its simplicity, computational efficiency, and quick adaptation, this model is well suited for real-time applications. Amygdala, Orbitofrontal Cortex, Sensory Cortex, and Thalamus are the four main subsystems involved in emotional learning. However, there are numerous influencing components in the Limbic system of the human brain. Moreover, BEL's network model algorithm is depicted in Figure 2.

Two input signals are used to compute this network: sensory inputs and reward. After that, Thalamus receives sensory input (SI) and pre-processes it before sending it to Amygdala and sensory cortex. Based on (8), (9), the output of the Amygdala and Orbitofrontal Cortex are determined as the weighted pre-processed signals. Furthermore, the network's output is the difference between these two signals (10) which has been interpreted as the control effort u. In the Amygdala and Orbitofrontal Cortex, learning takes place by referring to (11) and (12). Therefore, at each time step, both the reward and the SI are used to modify the gains in the Amygdala and the Orbitofrontal Cortex. The BEL algorithm is divided into two levels. In its first stage, as part of its function, the Amygdala learns to predict and respond to the emotional signal. Following that, the OFC examines the mismatch between the prediction and the actual signal received and adjusts accordingly [11]. Due to this, the Amygdala is responsible for immediate learning, and the OFC prevents the Amygdala from learning incorrectly [23]. Thus, reward and sensory input signals must be considered based on the criteria and other purposes.

$$\mathrm{MO} = \sum \mathrm{A_i} - \sum \mathrm{O_i} \tag{8}$$

$$O_i = S_i W_i \tag{9}$$

$$A_i = S_i V_i \tag{10}$$

$$\Delta V_i = \alpha S_i \max(Rew - \sum A_i) \tag{11}$$

$$\Delta W_i = \beta S_i (\sum A_i - \sum O_i - A_{th} - \mathrm{Rew}) \tag{12}$$

$$A_{th} = \max(S_i) \tag{13}$$

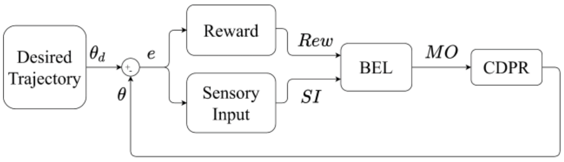
where, A_i, O_i are the Amygdala and OFC's output, respectively. Furthermore, S_i describes the SI signal, V_i, W_i denote the Amygdala and OFC's weights for the i^{th} node. There is a maximum of SI signals sent directly to the Amygdala via (12). Moreover, α and β are the Amygdala and the OFC's learning rates. As stated by equations (8) and (9), the difference of V_i must be positive, meaning that emotional memories become permanent. Alternatively, W_i is capable of rising and falling which means that it can react to Amygdala behavior when it is not appropriate. Because of this simple learning mechanism, it can represent quick adaptation as well as low computational complexity.

BELBIC not only rejects disturbances and handles uncertainty more efficiently than most other intelligent controllers, but it has a simple structure as well [24]–[26]. In other words, goals and the information necessary to control the system are provided via Rew and SI signals. Therefore, the adaptation rate and errors in tracking problems can be reduced by adjusting these signals. This approach has the benefit of low computation costs, quick adaptation, and robustness, but one major disadvantage is that it is not systematic in establishing learning functions and learning rates. As a result, these functions' structure and the coefficient can vary from one case study to another one.

Based on this research's objective, the saturation functions are used to define the learning functions as equations (13) and (14), to keep the learning signals limited and the cable forces positive. Both Reward and SI functions are determined only by joint errors, as demonstrated in Figure 3 and the following equations demonstrate that the controller is designed entirely in joint space and that there is no need for the Jacobian matrix.

$$\mathrm{Rew} = \left(1 + \exp\left(a_{\mathrm{Rew}}\left(K_{1_{Rew}} e + K_{2_{Rew}} \frac{de}{dt}\right)\right)\right)^{-1} \tag{14}$$

$$SI = \left(1 + \exp\left(a_{SI}\left(K_{1_{SI}} e + K_{2_{SI}} \frac{de}{dt} + K_{3_{SI}} \int edt\right)\right)\right)^{-1} \tag{15}$$



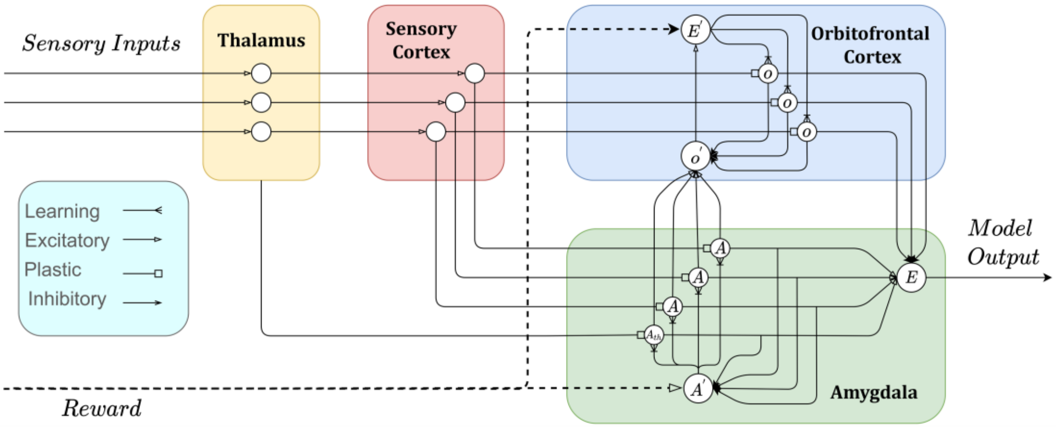


Figure 2. The BEL structure as a network.

Figure 3. The proposed controller's block diagram.

4. Experimental Results

The following parts describe the robot's structural details and experimental outcomes. The first part discusses its mechanical and control aspects. Following this, the robot's tracking performance is analyzed using the developed control method.

4.1. Kamal-ol-molk Robot

Throughout this section, the mechanical and control structures of the case study are briefly described, see [21], [27] for more information. Figure 4 depicts the two degree-of-freedom Kamal-ol-molk robot, which is controlled by eight cables and three actuators. A description of the robot's physical parameters is presented in Table 1.

Table 1. Dynamic and geometric properties of the CDPR.

Parameter	Symbol	value	dimension
Moving Platform mass	m	0.5	Kg
Moment of inertia	I_z	≈ 0	$Kg.m^2$
Radius of drum	r	3.25	cm
Length	c	216	cm
Width	d	180	cm

Each winch is mounted on the base frame, along with an actuator and a customized drum. To create the parallelogram links as shown in Figure 5, the fixed pulleys and the movable pulleys on the moving platform are in a particular configuration. Consequently, the moving platform has only two translational degrees of freedom in the plane of $x-y$. Figure 6 demonstrates hardware in the loop (HIL) setup for the real-time control setup. Furthermore, the host PC component makes it easy to modify the control law and the target PC acts as a real-time computing device that runs simulations using MATLAB-Simulink and communicates through Input/Outputs ports. Apart from that, to transmit motor commands and to receive information from encoders, this PC also includes PCI data acquisition boards [28]. As a solution to high performance, motors must be used in control loops as a highly effective force source. It might not be possible in real-world problems without an inner loop that includes a force sensor and the required force controller [29].

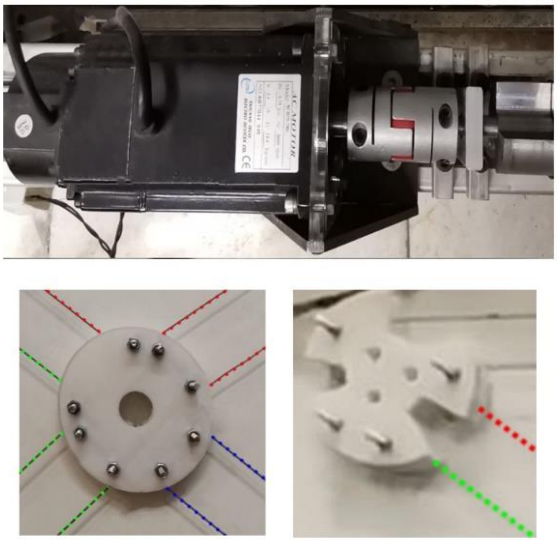


Figure 4. Components of the CDPR.

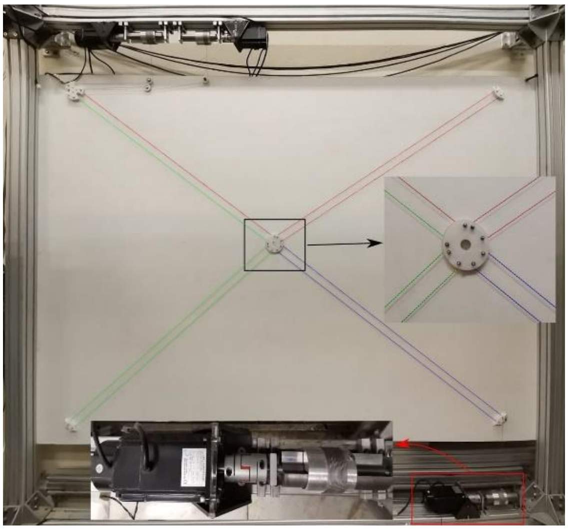


Figure 5. The 2-DOF fully-constrained planar CDPR driven by three AC motors via eight cable segments, Kamal-ol-molk plotter robot.

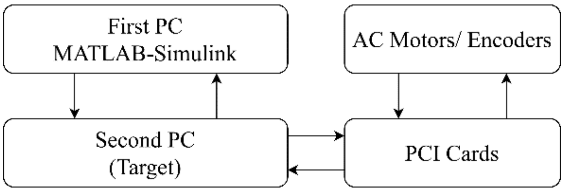


Figure 6. Block diagram of the experimental platform.

In the context of a parallel robot, the design of a controller can be more precise, but it involves the calculation of the pose of an end effector using forward kinematics or measuring it by external sensors. In contrast, controlling a parallel robot in the joint space may be more economical since the end-effector pose does not need to be measured or calculated, however, accuracy can be compromised because of the uncertainty of the inverse kinematic parameters. Furthermore, the CDPR requires the computation of the Jacobian matrix null space to compute the cable tension distribution based on the positive force constraint. Using the proposed method, only joint angles and inverse kinematics are required, which means no kinematics calculations and dynamic models are required.

4.2. Results

The experimental implementation of the proposed controller is discussed and reported in this section. To accomplish this, the moving platform must follow a circular desired trajectory around its central position. By utilizing the unique and easily implementable inverse kinematics model, the reference trajectory in task space is converted into the joint space trajectory.

Table 2. Parameters of the learning controller.

Parameter	value	Parameter	value
α	0.5	β	0.5
W_0	4	V_0	4
a_{Rew}	0.2	a_{SI}	1
$K_{1_{SI}}$	12	$K_{1_{Rew}}$	8
$K_{2_{SI}}$	0.1	$K_{2_{Rew}}$	0.1
$K_{3_{SI}}$	0.8	V_{th}	4

Figure 7 shows the tracking performance and the pre-defined trajectory of the robot under the proposed method for each joint. Subsequently, Figure 8 also illustrates the tracking errors. Errors in joint space are maintained in the range $(-10^{\circ}, +10^{\circ})$, whereas joint variables are variable between -1000° and $+1000^{\circ}$. This means that the tracking error can be considered satisfactory. A description of the parameters of the controller can be found in Table 2, which includes the initial weights of BEL, the initial learning rates, and the coefficients of the learning functions.

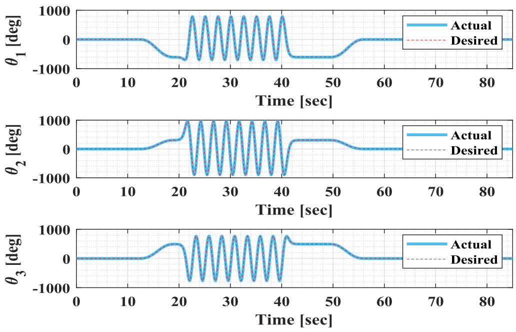


Figure 7. The performance of the developed method: reference and actual trajectories in joint space [deg].

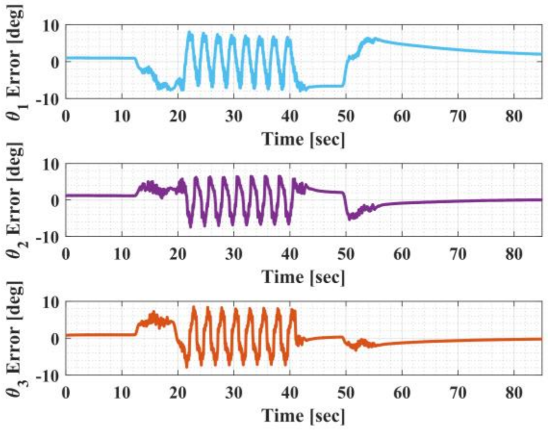


Figure 8. The tracking error using the proposed method in joint space [deg].

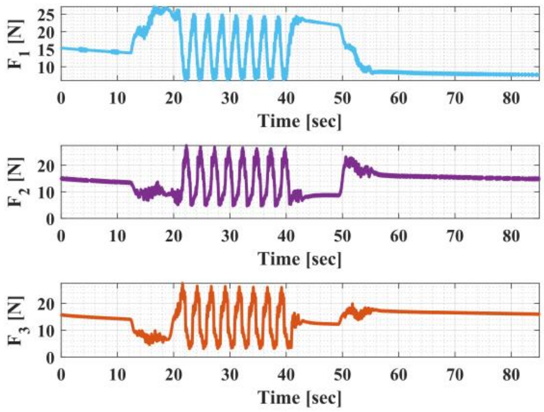


Figure 9. The force on cables produced by the proposed method [N].

Additional information on the control efforts is provided in Figure 9. As was discussed earlier, the cable forces are kept positive by defining the learning function properly. Lastly, the reference and actual paths of the proposed method are shown in the task space via Figure 10.

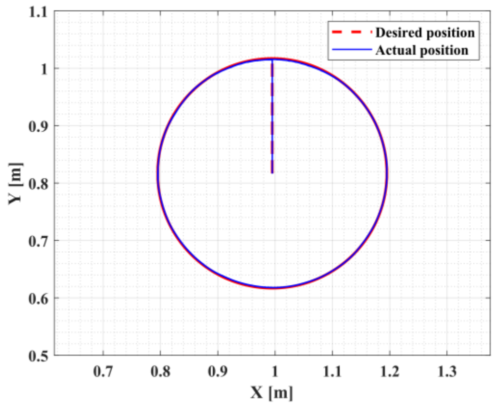


Figure 10. The reference and actual paths followed by

the robot in the x-y plane [m].

Additionally, Figure 11 illustrates the controller weights during the test. Accordingly, the network's gains adjust and modify rapidly as the desired trajectory changes.

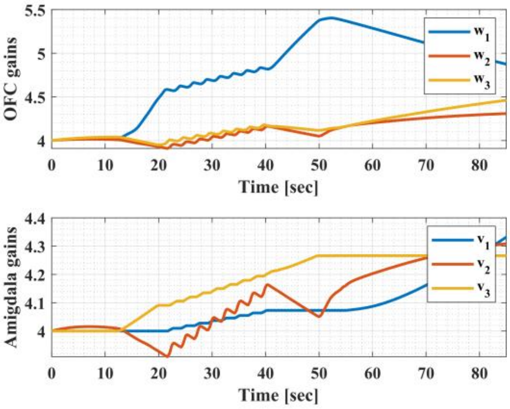


Figure 11. The evolution of OFC and Amygdala's gains through the test.

5. Conclusions

In conclusion, our research has introduced BELBIC, an intelligent control system tailored for fully-constrained Cable-Driven Parallel Robots (CDPRs), exemplified by Kamal-ol-molk II. BELBIC displays robust performance, ensuring positive cable tension regardless of the robot's Jacobian matrix or task variables. We have leveraged bounded functions like sigmoid functions effectively for reward and sensory input functions, enhancing the system's ability to regulate and optimize the robot's behavior efficiently. With low computational complexity, BELBIC proves to be a practical solution for real-world applications. Looking forward, we acknowledge the need for a comprehensive stability analysis of our proposed algorithm. Additionally, we emphasize the significant potential for optimization, including refining the reward function, parameter tuning, and learning rate adjustments. Such improvements stand to further enhance the CDPR's tracking performance, solidifying BELBIC's role as an intelligent control system suitable for fully-constrained CDPRs like Kamal-ol-molk II.

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Biography

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