Controlling a rehabilitation robot using intelligent control based on brain emotional learning

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Abstract

Due to the fact that patients lose their mobility due to a stroke or spinal cord injury, the physiotherapy process is essential, and due to the time-consuming and high cost of physiotherapy and improving the quality of treatment, rehabilitation robots are one of the various types of robots that are used in the treatment of disabilities.

Since the patient's injured limb is completely at the disposal of the robot during the treatment, the robot must ensure the patient's safety and control the patient's involuntary and unpredictable movement.

Therefore, controlling robots is an important and sensitive issue. In this treatise, rehabilitation robots of the external skeleton type (two-level planar robot) will be examined. The control strategy is a passive control type, and in its implementation, an intelligent controller based on emotional learning of the brain (BELBIC) has been used.

One of the most important causes of disability of people in different societies is the disabilities caused by stroke and spinal cord injuries.

According to the studies conducted, every year in America, about 252,222 people suffer from various types of strokes, especially brain strokes, of which about 400,000 people are saved from death and eventually suffer disability and paralysis of at least one or more body parts [1].

In the case of stroke patients, most of the disabilities are related to the movements and functions of the legs. According to the researches, rehabilitation treatments for semi-paralyzed people with spinal cord injuries require an average time between 6 months and two years, and in many cases, evaluations and examinations and treatment should continue for many years

In this regard, today the use of robots with the ability to create an intelligent pattern suitable for each patient has received special attention.

Keywords: Rehabilitation robot, Emotional Learning, Exoskeleton, BELBIC

1.Introduction

Rehabilitation of the injured limb

Rehabilitation is an activity in which the goal is to empower disabled people in order to reach the minimum level of physical and mental activity that is necessary in society.

In general, the aim of physiotherapy exercises is to improve the range of motion of the patient's joints (ROM), reduce muscle resistance, coordinate movement9 and the patient's balance.

At first, it was thought that the nervous system would not be able to relearn the movement patterns of the injured limb after being injured.

But research in the field of neuroscience has rejected this theory and it has been proven that if the neurons in which walking patterns are already stored are damaged, other neurons can take over this task.[2]

Classification of rehabilitative robots

Rehabilitative robots are classified on three bases, one is based on the treatment area, the second is based on the purpose of use, and the third is based on how to interact with the patient. In the field of therapy, rehabilitation robots are divided into two groups: upper body and lower body.

Upper body robots are generally used to restore mobility in the shoulder, forearm, or fingers. On the other hand, lower body robots are used to restore the mobility of knees, thighs, hips, wrists, and soles of the feet. The difference between upper body and lower body rehabilitation is that the weight of the body is on the lower body and it plays a role in losing the balance of the lower body. The upper body robot has more precise control, but the lower body robot's dynamics must be precise.

In the second division, the rehabilitation robots are divided into two groups: collaborators and therapists. Collaborative robots, such as the Johns Hopkins robot, help the patient perform activities of daily living without therapeutic motivation. But therapeutic robots are used to increase the patient's movement ability.

In the third classification, rehabilitative robots are divided into two groups: exoskeleton and final operator. The exoskeleton is a robot that is made in the shape of a body part and is connected to the disabled part at several points and moves it along with it. Exoskeleton robots are made in the shape of the anatomy of the body and are attached to the organ at several points. In contrast to the external skeleton, the final effector must be mentioned, which is connected to the disabled member at only one point.

A review of past work on robotic foot rehabilitation

The designs that have been developed so far in the world for the rehabilitation of the lower limbs of physically disabled patients can be examined based on the mechanism's performance area.

A: The first category are mechanisms in which external skeletons are used

Three important plans in this field are Lokomat robotics, ALEX robotics and LOPES robotics.

Figure ۱ lokomat robotics

Lokomat robotic set: This robotic set is the most famous design in the field of lower limb rehabilitation (Figure 1).

It is manufactured by Hokuma company in Switzerland and is commercially available in the market today. In this design, the movement of each of the hip, knee and ankle joints is controlled by a separate electric actuator. Also, a degree of freedom is considered for the vertical movement of the upper body, for which the necessary force is provided by a pneumatic operator, and the amount of this force can be adjusted and adjusted by an active control system.

This rehabilitation device was built at the University of Delaware. In figure (2) the image of this device: ALEX robotic set is shown [4]. In addition to the degrees of freedom related to movement in the sagittal plane, this device has the ability to create horizontal movement in the frontal plane, the ability to rotate the upper body around the vertical axis, and the ability to create adduction and abduction movements in the hip joint.

2Figure ALEX robotics

LOPES Robotics Collection

This robot was made at the University of Twente in the Netherlands and has the ability to move the whole body in front-back and left-right directions. Figure 3.

The weight is passively restrained by a four-bar mechanism. In order to increase the performance quality of the control system, series elastic actuators have been used in this robot[5].

3Figure LOPES robotics

For example, the movement ranges of robot degrees of freedom are given in table (۱-۱)

Degree of freedom	Rang of motion	Maximum torque/force	Maximum speed
Hip abduction	+15° / -15°	30 Nm	1 rad/s
Hip flexion	+60° / -30°	65 Nm	2 rad/s
Knee flexion	+0° / - 90°	65 Nm	5rad/s
Sideways	+0.30m/-0.30m	250 N	0.5 m/s
For-/back-ward	+0.35m/-0.35m	200 N	0.5 m/s
Up/down	+0.10m/-0.10m	Passively weight compensated	-

Table (1-1) movement ranges of the degrees of freedom of the LOPEZ robot [5]

The device made by the research group of the University of Berlin Figure4

B: The second category are mechanisms in which moving plates are used under the soles of the patient's feet

In these mechanisms, by planning the movement of the moving plate, the whole leg or a part of it is forced to move or they are helped in creating desired movements. Figure (4)

Rehabilitation robot of Khajeh Nasir University: Considering the need in the country to use robots for rehabilitation and considering the very high price of foreign commercial models such as Lokomat robotic set, the design and construction project of rehabilitation robotic set at Khajeh University of Technology Nasir al-Din Tusi has been done Figure (5)

Figure5 Rehabilitation robot of Khajeh Nasir University

This design includes two parallel Stewart robots to create movement from under the soles of the feet, two lateral robots to guide the movement of the upper degrees of freedom in coordination with the movement of the lower degrees of freedom, and an active weight restraint mechanism.

Stewart robot actuators are of pneumatic type, whose range of motion is according to the working space required to cover the walking kinematics, the diameter of the cylinder according to the required forces that the actuators must create, and the characteristics of the valves according to the required air flow rate. It is chosen to create the necessary speeds [7].

Control strategies in robotic leg rehabilitation

Based on different control methods and control strategies, it has been used in the field of foot rehabilitation, which we will discuss briefly.

Position control on fixed tracks

As mentioned, the simplest and most basic method to rehabilitate the injured limb is to guide the limb on a predetermined path, or in other words to control its position. The most important point to make the position control method effective is to determine the appropriate reference paths for movement, which is a research topic in itself. In this regard, reference paths can be fixed or variable. Fixed reference path means that the path is fixed in the geometric space and also the time of the path is fixed.

For this purpose, it is possible to use mathematical models of route determination, such as the route with the lowest rate of change of acceleration. This type of path was presented by Hogan and Flash to determine the path of hand movement. [8] It is based on the principle that in this path, the third time derivative is the minimum position. This type of path is popular because having the length of the path and the period of its movement, it can be defined as an analytical function of time. MIT-Manus rehabilitation systems in reference [9] and ARM-Guide in reference [10] have used this type of path as their reference path.

Of course, due to the fact that this type of path does not cover many natural daily movements of the hands and feet.[11] It is necessary to design and use other types of paths. Based on another idea, the paths traveled by the organs of healthy people can be used as a reference path. [4,11,12]

Impedance control

The basic idea in using the impedance control method in robotic rehabilitation is to allow the patient some deviation from the original reference path and the patient himself tries to return his limb on the original path. The permissible amount of deviation also depends on the ability of the patient. Accordingly, in [5], [4] and [13], the amount of force applied by the robot changes according to the amount of deviation or movement speed.

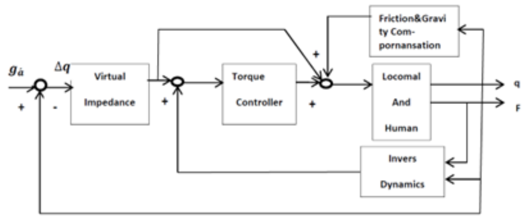

Figure 6- The structure of the impedance control system presented for the Lokomat robot [14]

Admittance control

Robots with admittance control can provide significant stiffness and low friction. Controlled admittance is useful for gradual rehabilitation with many degrees of freedom. High gain position controls can compensate for friction in joints. Admittance control has been used by Columbo and his colleagues to control the admittance of locomat robot. [14] The advantage of using this method is that it encourages the patient to start moving, which is an important factor in accelerating the rehabilitation process from the point of view of the central nervous system. [15]

Emotional control

During the last few years, man as a biological model, feeling and knowing are two important aspects of his mental life. Therefore, during the last few years, there has been an increase in interest in the development of a computational model for emotion [21] until finally, Morne and Baknius presented an article entitled the computational model of emotional learning in 2000, which is the reference method for this work to this day. which includes parts such as amygdala, orbitofrontal, sensory cortex and thalamus [44,43] and was provided to engineers as a model. to use it in the design of controllers and learning machines. Based on this, intelligent control was introduced based on the emotional learning of the brain (BELBIC). [32]

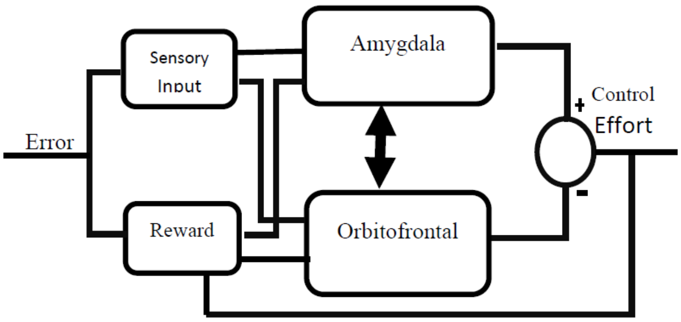

Figure 7- Control system based on emotional learning

In 1996, Kobayashi used emotional learning in decision making [63]. And in 2001, Fetorchi used BELBIC to reduce the maximum control error. [32] Also, in the same year, Fetorchi and his colleagues used BELBIC to reduce the control effort. [33]

Kinesiology and biomechanics

In order to control robots that deal with movement organs and walking patterns, we need to be familiar with the mechanics of body movements, terms and basics of kinesiology. The joints of the body are divided into three categories in terms of movement, non-movable joints, semi-movable joints and movable joints. There are two types of movement restrictions for joints: the first type is the movement restriction in people who do not exercise and their range of movement is reduced due to not exercising, the second is the movement restriction that exists naturally in the joints and is the same for all people.

Robot dynamics

Using a robot in the field of physiotherapy must be under the supervision of a physiotherapist. The most important feature expected from the used robot is not harming the patient, having the ability to create the necessary movements and having the ability to interact with the patient and the therapist. Therefore, it is very important to design devices that can intelligently help in the rehabilitation process and be effective.

Two degrees of freedom mechanism

The leg rehabilitation robot is an exoskeleton type, which is a plate mechanism that includes two rigid arms that are connected by hinged joints without friction and damping effects. And the second arm connected to the knee and leg to create flexion and extension movement around the frontal axis (in the sagittal plane) can be seen in Figure 8, a simple model of a two-degree robot.

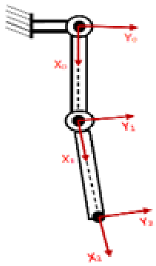

Figure 8- Robot with two degrees of freedom

The geometric parameters and the mass of the two degrees of freedom robot arms are given in table (2) and the number of the arms is from 4 to 2, respectively: the arm connected to the thigh, the arm connected to the knee

شماره بازو	M(kg)	L(m)	I_{zz}
1	0.8	0.5	I_{zz_1}
2	1.66	0.5	I_{zz_2}

Table 2. The values of the geometric parameters and the mass of the arms

Kinematic analysis

- Denavit-Hottenberg parameters
  Considering that each robot arm can be defined kinematically with four quantities. In the case where the joint is hinged, the joint variable, and the other three parameters are called fixed parameters of the arm. According to the placement of coordinate devices and Hartenberg's rules, Hartenberg's parameters are extracted as follows:

Joint	a_i	α_i	d_i	θ_i
1	l_1	0	0	θ_1
2	l_2	0	0	θ_2

Table 3 Denavit-Hartenberg parameters

Transfer matrices

$$^{0}T_1 = \begin{bmatrix} 1 & 0 & 0 & l_1 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$^{1}T_2 = \begin{bmatrix} 1 & 0 & 0 & l_2 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Jacobian matrix of the robot

$$^{0}j(\theta) = \begin{bmatrix} -l_1S_1 - l_2S_{12} & -l_2S_{12} \\ l_1C_1 + l_2C_{12} & l_2C_{12} \end{bmatrix}$$

Dynamic analysis

Derivation of dynamic equations

In the first type of problem, having the characteristics of (a point of the robot's path, we want to obtain the vector of joint moments τ. The dynamic relationship used to solve this type of problem will be beneficial in controlling robot arms. In the second problem, how the robot mechanism moves as a result of applying a set of joint torques will be calculated. In other words, the values are calculated (by having the torque vector τ.

Equations of motion

During the movement of the robot, the two degrees of freedom of the equations governing the movement are expressed as the following equation.

$$M(\theta)\ddot{\theta} + V(\theta, \dot{\theta}) + G(\theta) = \tau$$

Dynamic simulation

For the dynamic simulation of the robot, we must use the dynamic model.

$$\ddot{\theta} = M^{-1}(\theta)\left[\tau - V(\theta,\dot{\theta}) - G(\theta) - F(\theta,\dot{\theta})\right]$$

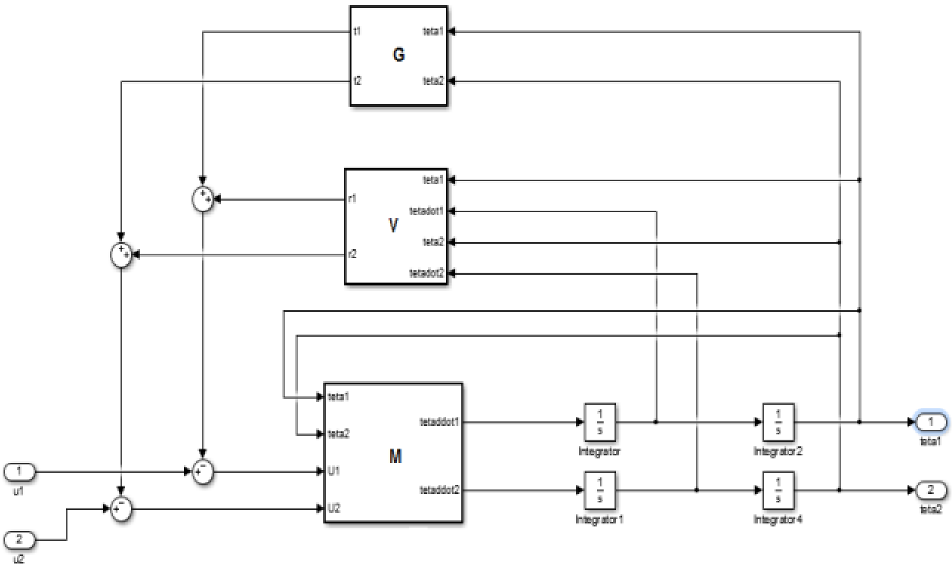

Figure 9- Dynamic modeling of the robot

2.Method and Material

Intelligent control based on emotional learning

In recent years, the design of intelligent systems has attracted a lot of attention, control techniques based on neural network [34], fuzzy control [35] and genetic algorithm [36] are among them. Emotional learning is a psychologically motivated algorithm that includes a family of intelligent algorithms. [37] Emotion modeling has attracted a lot of attention in the fields of cognitive psychology and intelligent systems design. Apart from the negative role of emotions in decision-making, emotions have a powerful tool in creating quick and satisfying decisions. Also, biologically motivated intelligent computing has been successfully used to solve various types of problems.

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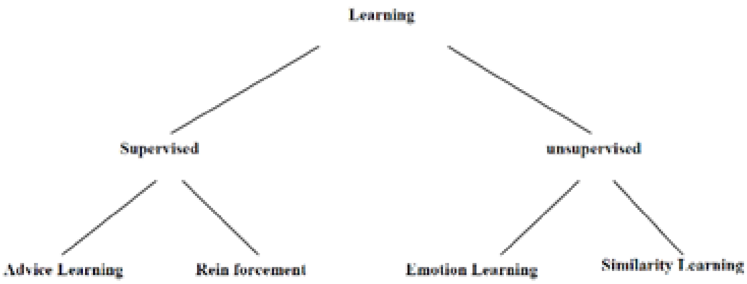


Figure 10- Division of learning systems

Emotional learning is one of the emotional learning strategies based on emotional evaluations in the brain of mammals. This learning process takes place in the (limbic) system of the brain. [42] Emotions that originate in the cerebellum of the midbrain are involved in decision-making [27, 28] It is now founded that regardless of the negative nature of emotions in biology, emotions are a very important positive force for intelligent behavior in natural and artificial systems.[۳۰،۲۹]

Architecture of the limbic system

The limbic system, as a part of the mammalian brain, is mainly responsible for emotional processes.

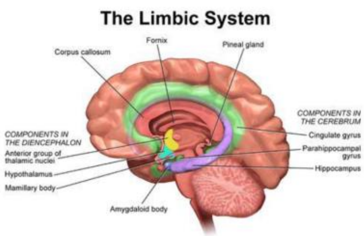


Figure 11- The general structure of the limbic system [49]

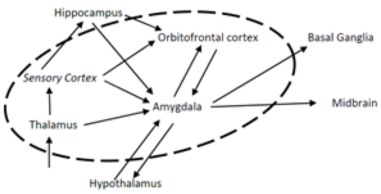


Figure 12- Connection with other components of the limbic system [44]

An emotional stimulus and its emotional value are related in the almond-shaped area of the brain (amygdala) [۵۱،۵۰]

In the amygdala, emotional stimuli in the sensory cortices plus coarsely classified stimuli in the thalamus with emotional value are subjected to much analysis.

Formulation

The figure shows the emotional computational learning sub model. The model is divided into two parts. Amygdala and orbitofrontal. The amygdala receives its input from the thalamus and the sensory cortex, while the orbitofrontal receives inputs from the amygdala and the sensory cortex. The system also receives a reinforced signal (initial reward) from which it is unclear.

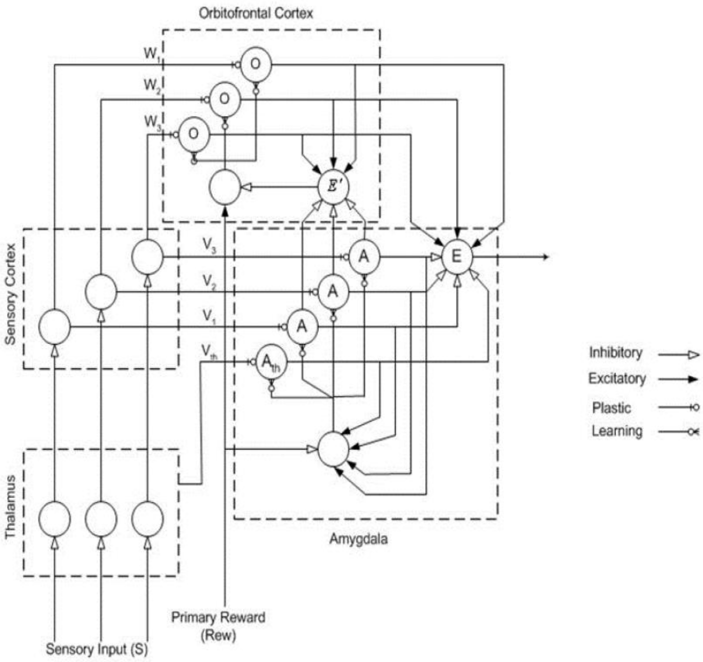


Figure 12- Graphic model of limbic system learning calculations [45]

Intelligent control based on emotional learning of the brain (BELBIC)

Based on the presented model, intelligent control based on the emotional learning of the BELBIC brain is presented based on different models. By Lux et al. [21,20], the basic structure of the emotional controller is shown in the figure below.

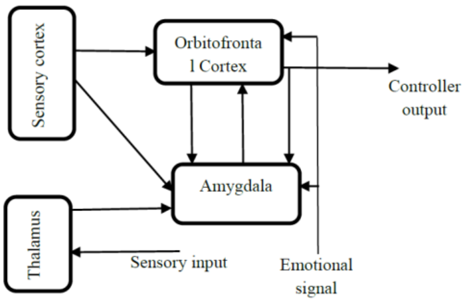


Figure 13- General structure of emotional control blocks [20]

The main idea in BELBIC is that when the system receives different categories of emotional signal it produces output in a way that reduces emotional stress and improves emotional rewards.

In BELBIC, the factors that the designer is sensitive to are considered as stimuli that cause anxiety in the system, and the control system must act in such a way that the anxiety is reduced. In emotional controllers, negative emotions such as fear, anger, and pain are used to train systems such as a moving robot[۲۲]

Shahmirzadi model

Shahmirzadi presented a new mathematical model to implement how emotion is involved in learning in the brain of living beings.[22] The main difference of this method is the addition of a delay block to the orbitofrontal and sensory cortex to improve the dynamic behavior of the controller. The delay value of these blocks is something that at first there is no view of it, and of course these values are not directly related to the delays of the system under control. The existence of these delays helps to distribute the reward signal in the system. Because the ideal time to apply the award is uncertain and these awards are applied in the vicinity of the ideal time.

The purpose of the Shahmirzadi model, which is an improved version of the luxu- Jamali model. Achieving faster responses along with reducing overshoot. Shahmirzadi's main motive is to increase the range of efficiency in controlling complex targets and systems. Systems with uncertain inherent delay or transform functions with zero minimum phase are among these cases. In the Shahmirzadi model, the effect of the sensory signal is of the first degree. The presence of a double connection between the amygdala and the orbitofrontal in the Shahmirzadi model leads to a precise control function and the selection of appropriate inhibitory signals through the orbitofrontal. which increases its resistance to sudden changes in responses.

One of the decisive issues and the most important part of working with BELBICis the correct selection of the reward function and sensory input.

Sensory inputs and reward signals can be arbitrary functions of system parameters, which should include coefficients of error (or outputs of the system being controlled), control effort, and their derivatives and integrals.

Sensory input is a type of control signal that encourages or punishes based on the reward signal. The reward function should be designed so that it has the lowest value in the most favorable situation[۳۱]

In general, the reward signal should include the concept of the desired state of the system, and the sensory input should introduce the factors to BELBIC that should be considered in the process of the system.

The application of BELBIC in rehabilitation robots

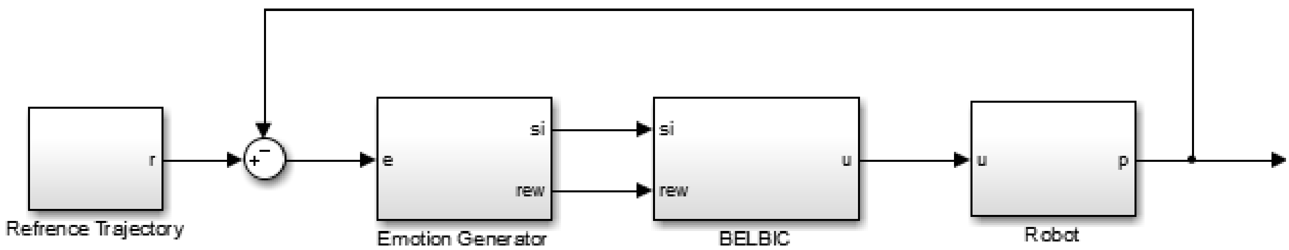


Figure 14- General diagram of the robot control system with blocks

Since the rehabilitation process is accompanied by repetition, the input must be intermittent and due to the need to perform computational operations in the path characteristic function system, it must be well-behaved and derivable. The control of Belbeck rehabilitation robot has better responses compared to PID. For rehabilitative robots, speed and accuracy of control are not very important. In addition to overshoot, the settling time of BELBICis less than PID.

The resistance of BELBIC

The ultimate goal of building rehabilitation robots is to use them in home and hospital environments.

According to the application, those who use these robots have different conditions. In the definition of robust control 4, it is said that if the control system works correctly with one set of parameters, it must also work correctly with another set of the same parameters. It should also handle modeling errors and system uncertainties. To all these cases, we must also add conflict. In BELBIC, the control rules are not changed based on the gradual change of the parameters, but the definition of the reward signal helps the system to progress to obtain the desired state of the system. BELBIC's resistance and versatility have classified it in the category of text-independent controllers 2.

In the BELBIC response, in places where the input change is in the form of a rapid jump or fall, a little difference and overshoot is observed, but in PID, in the places where the input change is in the form of a rapid jump or fall, the overshoot is more than the Belbeck along with fluctuations (second order)) it can be seen that in the case of noisy systems, Belbeck's performance is better than PID. BELBIC is a very robust and model-independent controller that is suitable for controlling uncertain and non-linear systems such as robots, and with highly non-linear inputs.

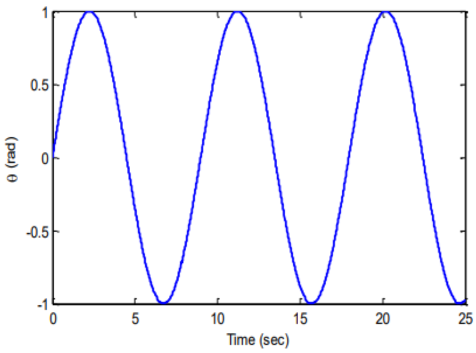


Figure 15- sinusoidal Input

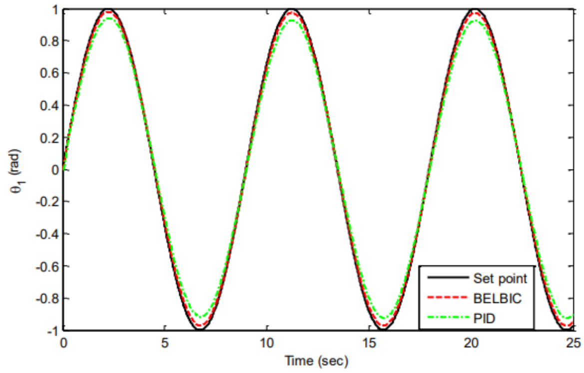


Figure 16- Comparing the first-order error curve in the control mode with PID and BELBIC

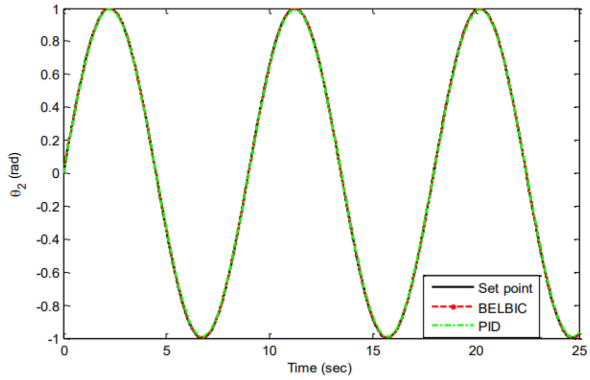
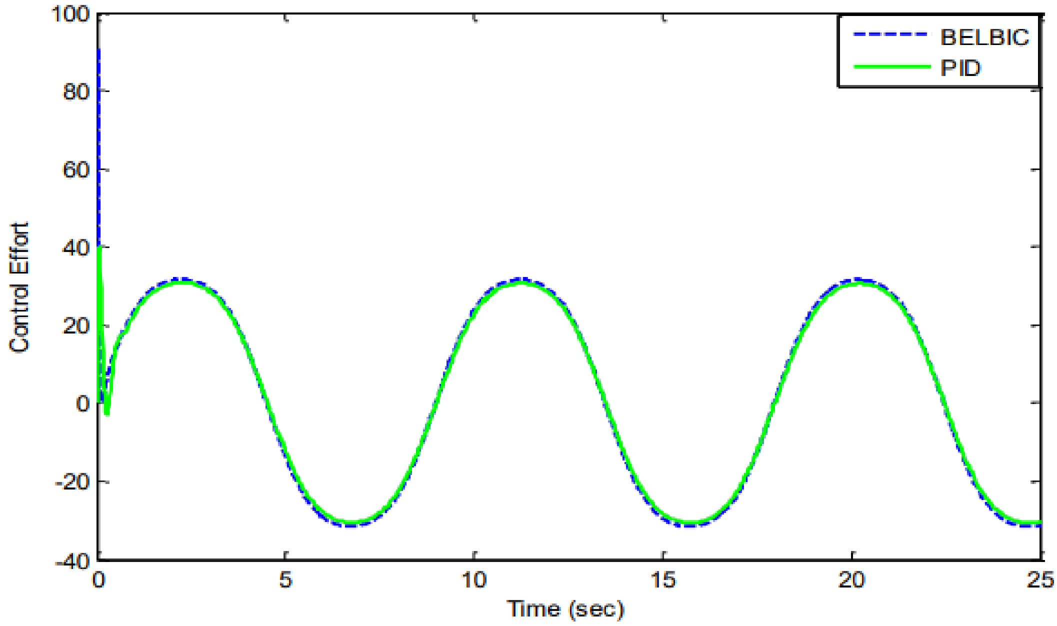


Figure 17- Comparison of quadratic error curve in control mode with PID and BELBIC



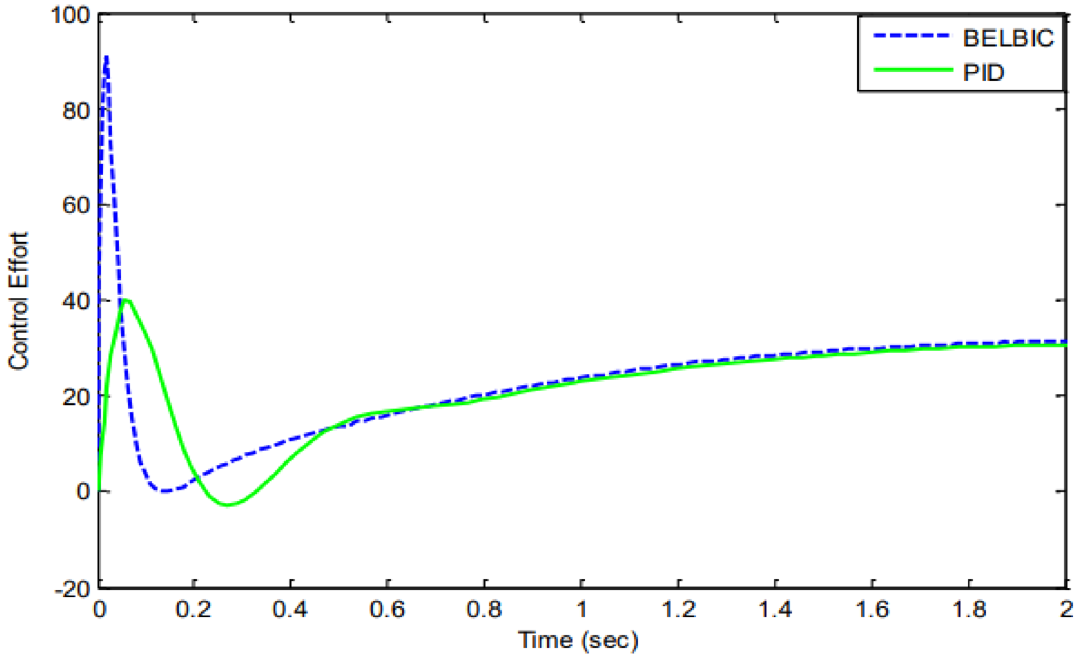


Figure 18- Comparison of the first-order control effort curve in control mode with PID and BELBIC

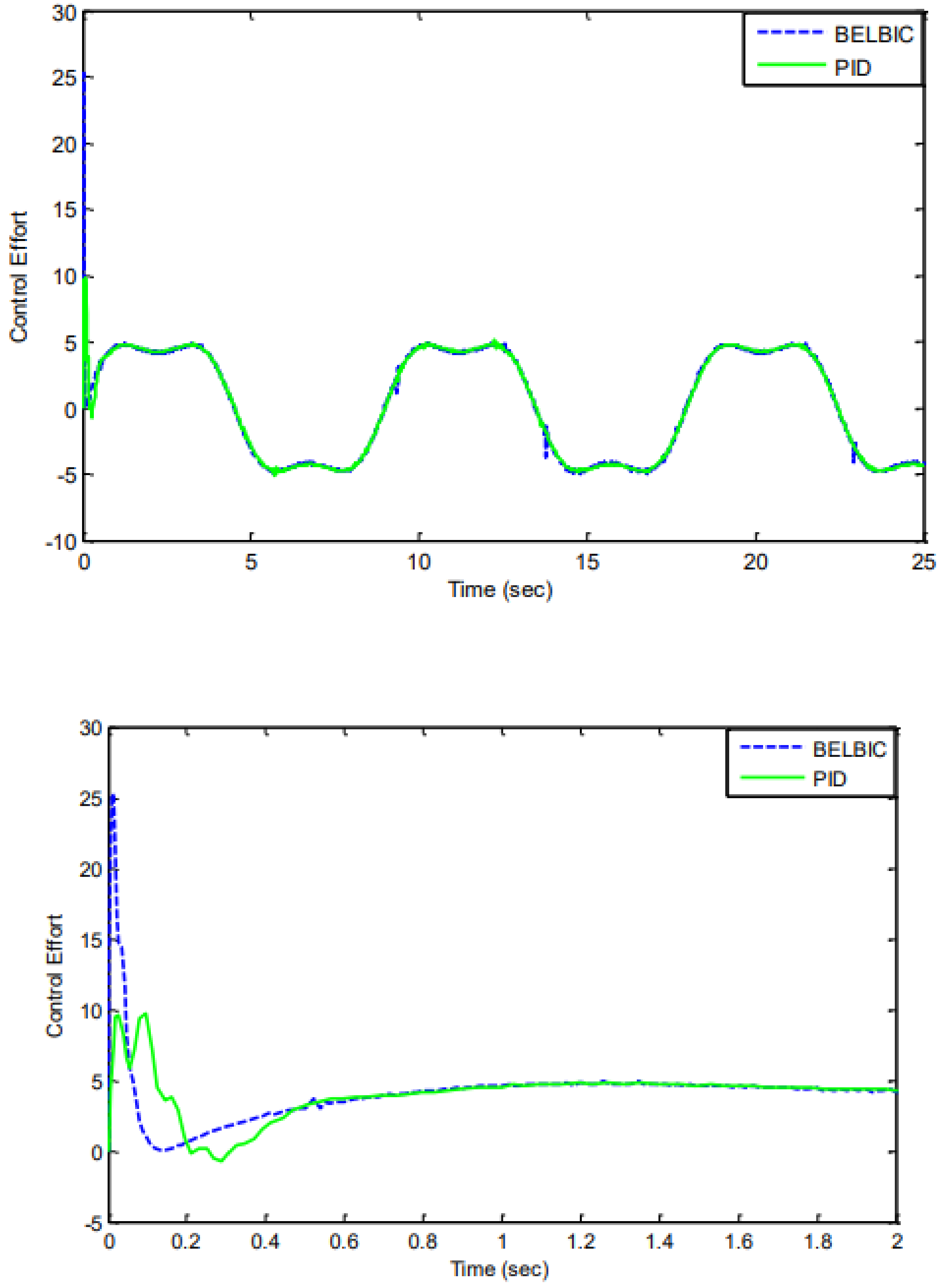


Figure 19- Comparison of the second-order control effort curve in control mode with PID and BELBIC

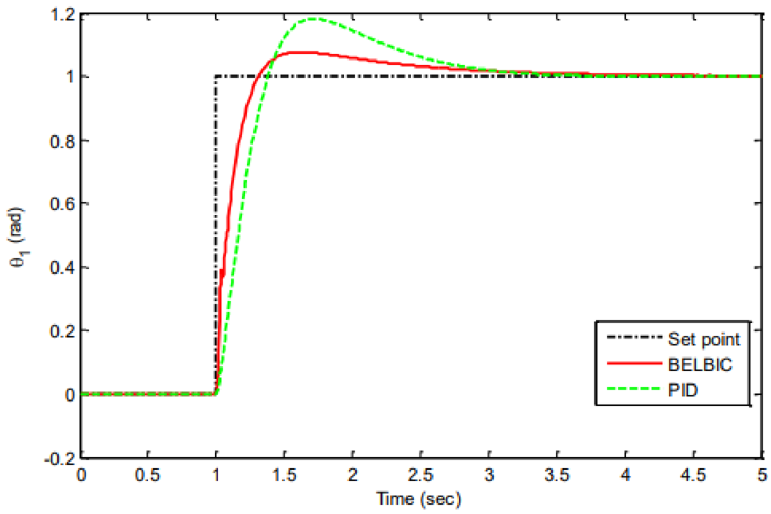


Figure 20 - Comparison of the first-order error curve to the step input in control mode with PID and Belbic

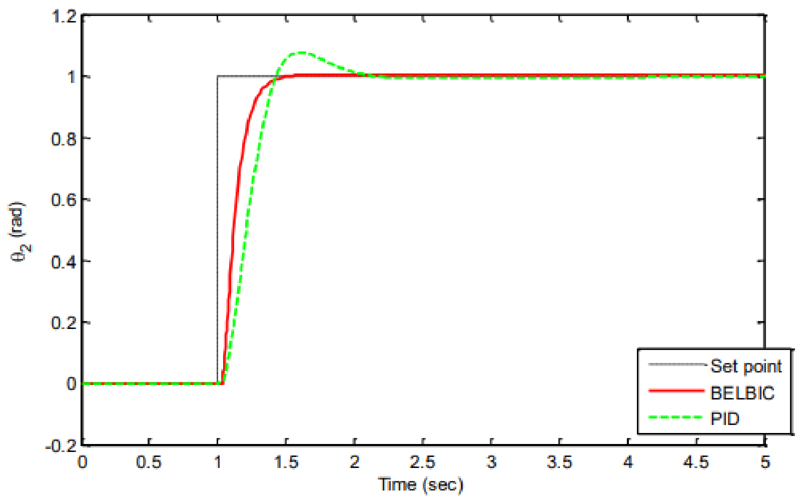


Figure 21 - Comparison of the second-order error curve to the step input in control mode with PID and Belbic

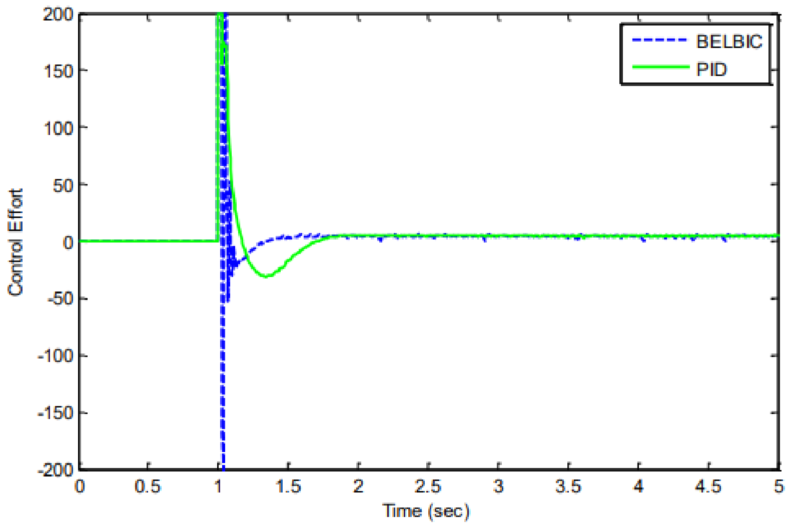


Figure 22 -Comparison of first-order control effort curve to step input in control mode with PID and Belbic

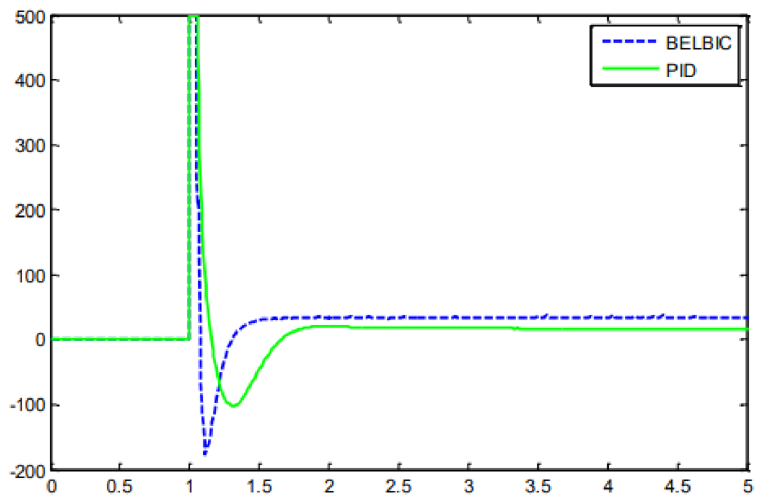


Figure 23 -Comparison of second-order control effort curve to step input in control mode with PID and Belbic

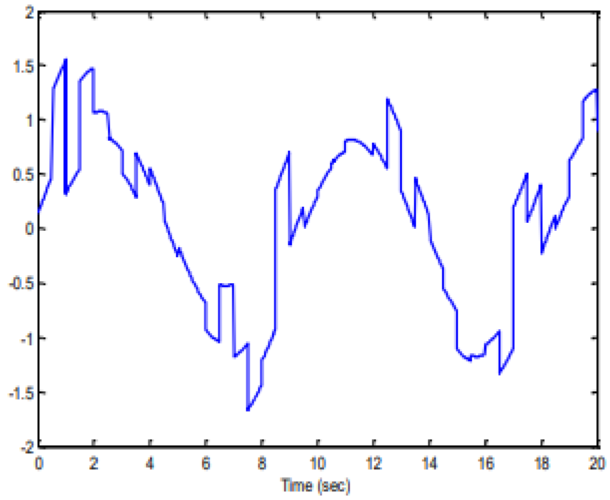


Figure 24- sine wave input with random noise

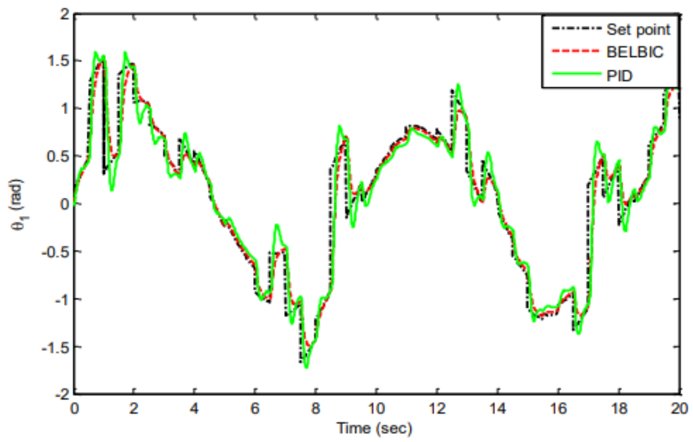


Figure 25- Comparison of first-order error curve to sinusoidal input with noise in control mode with PID and Belbic

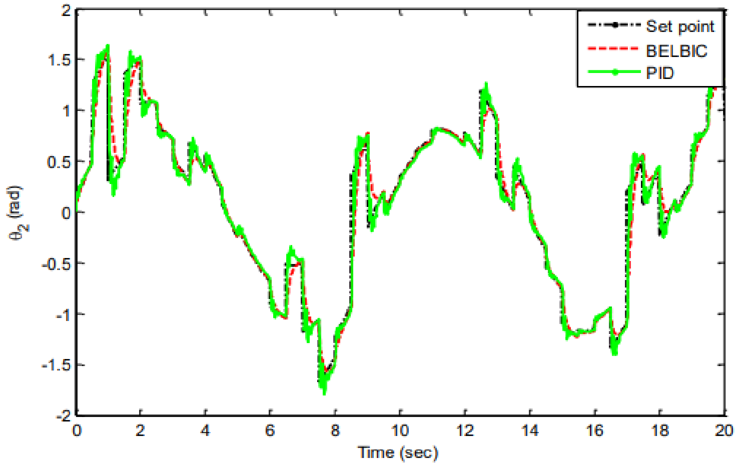


Figure 26 - Comparison of quadratic error curve to sinusoidal input with noise in control mode with PID and Belbic

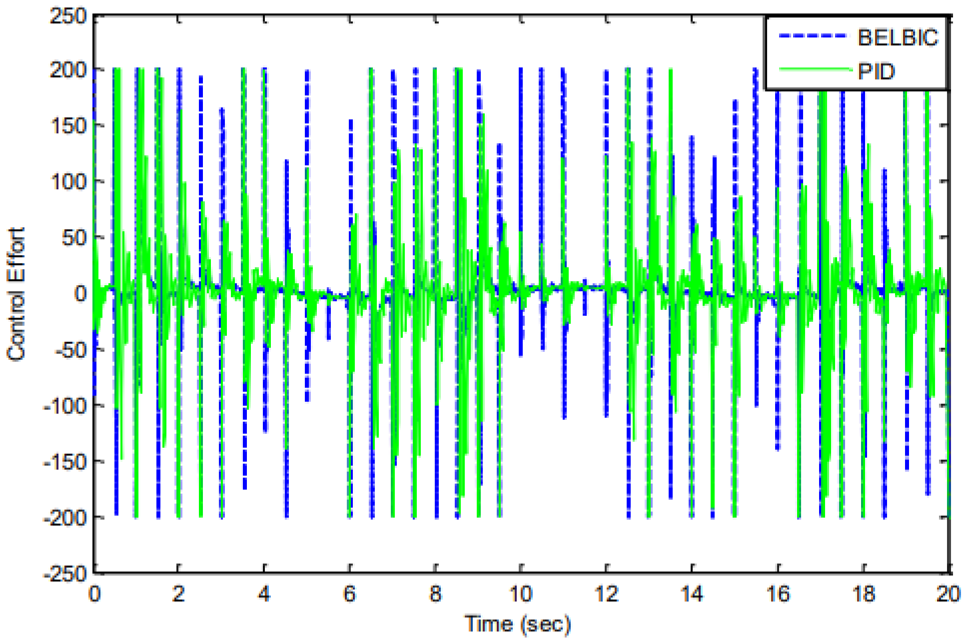


Figure 27- Comparison of first-order control effort curve to sinusoidal input with noise in control mode with PID and Belbic

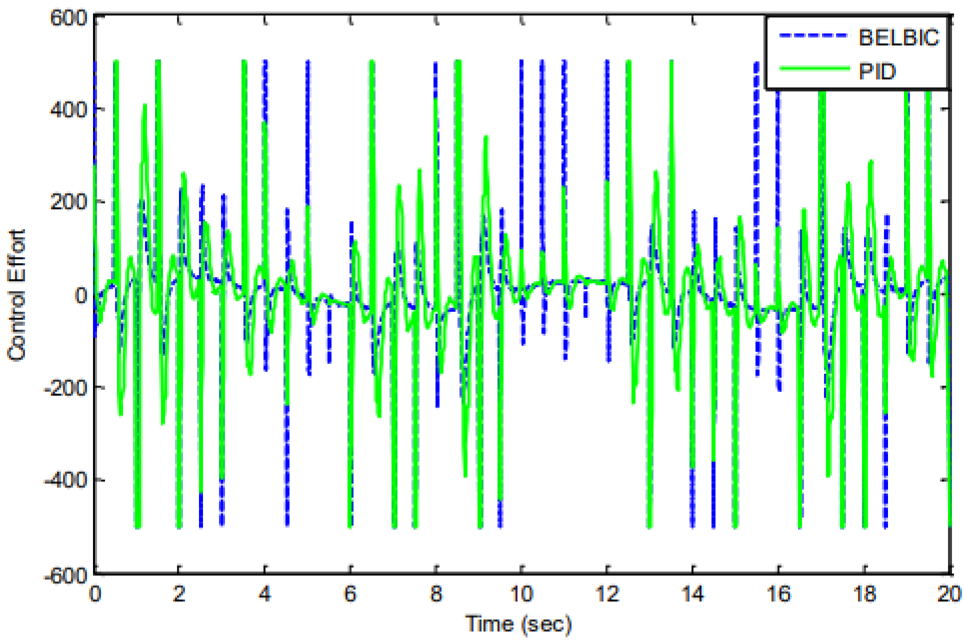


Figure 28- Comparison of quadratic control effort curve to sinusoidal input with noise in control mode with PID and Belbic

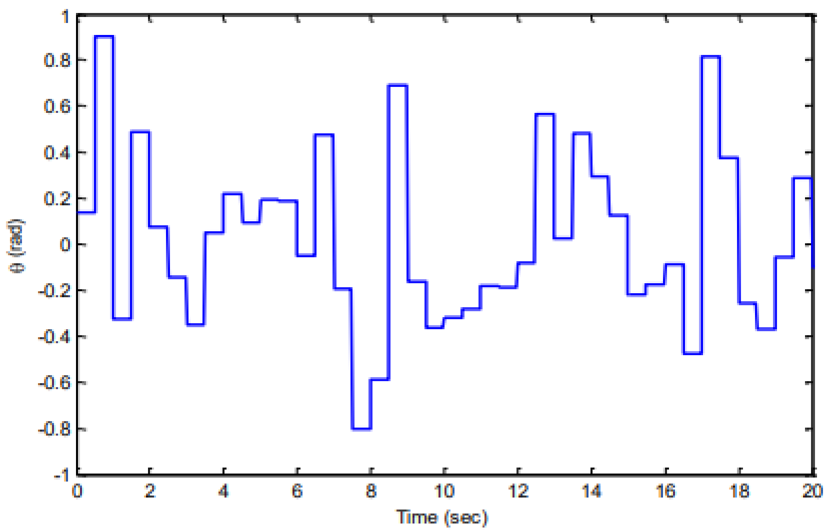


Figure 29- random input signal

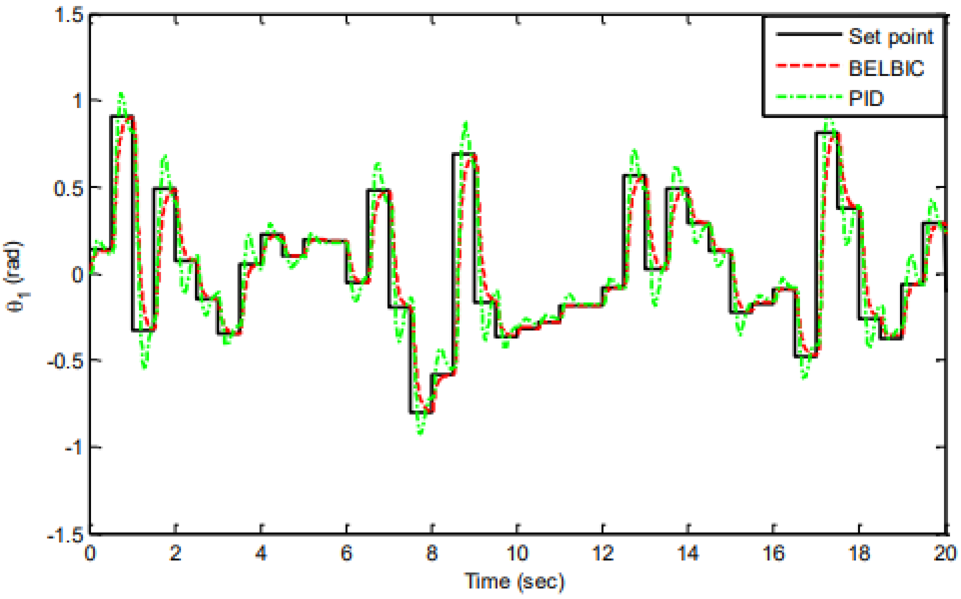


Figure 31- comparing the first-order error curve to random input in control mode with PID and Belbic

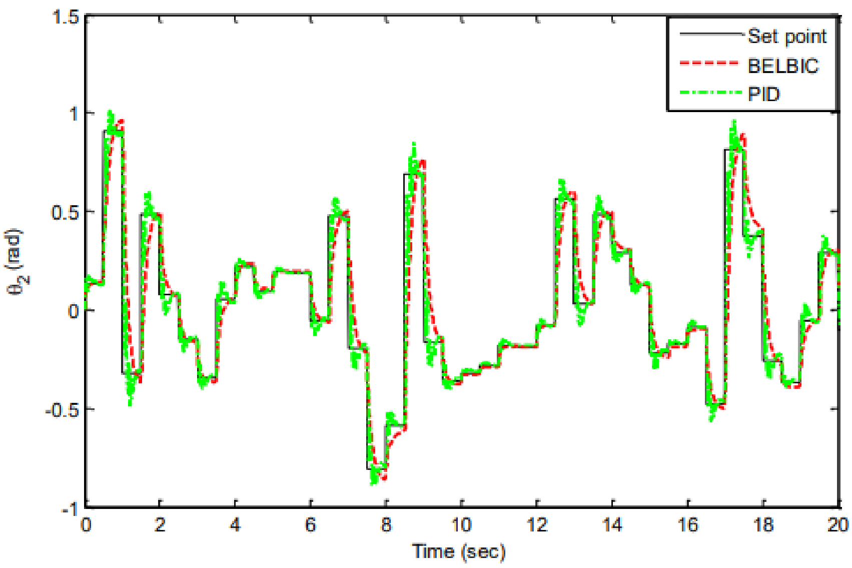


Figure 32- comparing quadratic error curve to random input in control mode with PID and Belbic

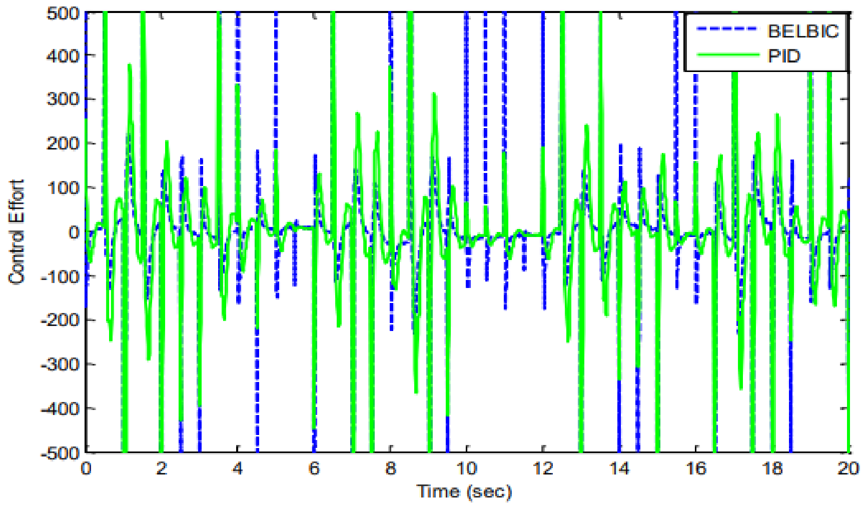


Figure 33-Comparison of first-order control effort curve to random input in control mode with PID and Belbic

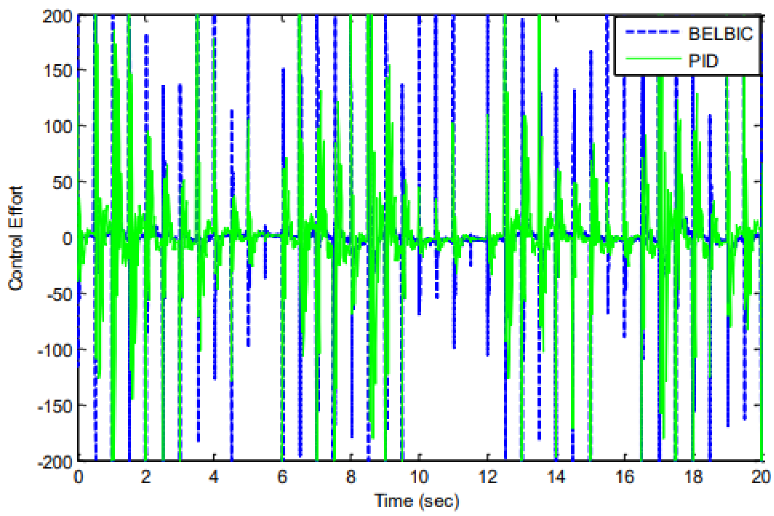


Figure 34- Comparison of quadratic control effort curve to random input in control mode with PID and Belbic

To simulate the patient's involuntary behavior during the treatment and compare the performance of the controller, we give a random input to the system.

The results show that in the response curve of the first and second degrees of freedom, the Belbic response corresponds to the input curve in most of the points and in the places where the input change was in the form of a rapid jump or fall, a slight difference and over jump is observed, but in

PID, in places where the input change is in the form of a jump or a fast fall, the overshoot is more than that of Belbic along with fluctuations.

(second degree) it can be seen that in the case of random input, Belbic had a better performance than a PID. Belbic's performance and

PID is not much different from the point of view of comparison of speed and accuracy. Belbic and PID control effort curve according to the set values

are similar to each other

3. Discussion

BELBIC is a model-independent adaptive controller for various complex systems.

Intelligent control of systems with unknown or uncertain dynamics or even variable dynamics has been carried out with Belbeck, even in some cases model-based methods do not work due to lack of information and data. BELBIC is used in decision making and control of simple systems and non-linear systems. The initial implementation of the computational model of the emotional learning method of the brain was not for control applications, and its purpose was to explain the way the brain works from a biological and psychological point of view. BELBIC advantage is that in modeling the system under control, the model can be considered very simple. Because the rest of the unmodeled components of the system are considered to be unmodeled dynamics. One of the notable features of this method is its simplicity in multi-purpose problems, low computational complexity, and its quick training in real-time control problems. Compared to other intelligent methods such as neurophase, it is much simpler and has less calculation volume. BELBIC can have several inputs but only one output.

Simulations have shown that, in dealing with the same problem, BELBIC has more resistance to noise and random input than PID.

4.Concollusion

In the works that have been done in the field of rehabilitation robots, the use of patient power in rehabilitation has always been emphasized, and because of the complexity of this work, the passive control method is still used in commercial robots.

For this reason, it is better to have a method for active control that works smoothly and without shock while considering the patient's movements.

Many things can be done to improve the idea of emotional learning and to strengthen emotional inputs and to reach a systematic method to calculate it, so that this new method becomes a well-known control method among intelligent methods based on nature. One of the tasks to improve this method is to realize about the stability of this method.

When talking about the dynamics of rehabilitation robots, it should be mentioned that the robot system is good because of its indeterminacy. used text-independent methods for control. Because the disabled member of the patient has reactions that make the system highly non-linear, uncertain and even unpredictable. In the field of emotional control modeling, it can be done.

Simple mathematical models that can be presented based on Morn-Buckenius theory. Being more compatible with computing systems can be effective in the expansion of BELBIC.

The use of active control methods to control rehabilitation robots to take into account the involuntary behavior of the patient under treatment, which includes impedance and admittance control and both methods respectively.

In general, rehabilitation robots are a new topic in treatment issues, and the improvement of its manufacturing and control technology can increase its use. It is hoped that future efforts will be in line with this goal.

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