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Neuro-fuzzy control of bilateral teleoperation system with transmission time delay and force feedback using Arduino Due board

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Original Research

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Abstract:

In this paper, an intelligent adaptive controller is designed to handle the transmission time delay problem in a complex and nonlinear bilateral teleoperation system with force feedback. The combination of the inference capacities of fuzzy logic reasoning and the learning capacities of neural networks, enable the formation of an adaptive and robust neuro-fuzzy controller ANFIS (Adaptive Neuro-Fuzzy Inference System) which adapts to variations in the dynamics of the system by the automatic adjustment of the parameters of the fuzzy rules and the membership functions using a learning algorithm, thus ensuring compensation of the negative effects of transmission delay in the closed loop system. Thanks to the speed and power of the microprocessor of the Arduino Due board and the functionalities of Matlab-Simulink, a real experimental platform of master-slave teleoperation system with transmission delay and force feedback is designed. In order to demonstrate the efficiency, adaptability and advantages of ANFIS controller, several comparative experiments are carried out using different controllers (ANFIS, conventional PI and PI regulator with the modified wave variable method PI+MWVM). The experimental results clearly show the high system performance achieved with the ANFIS controller.

Keywords: ANFIS; Arduino Due; Bilateral teleoperation; Stability; Time delay; Wave variables

1. Introduction

In today's life, bilateral teleoperation systems have become extremely important, thanks to their role in performing specific tasks remotely in a difficult or inaccessible environment [1] such as space maintenance, military applications, nuclear sites and medicine [2–4]. However, performing these tasks remotely causes transmission delay in communication channels, which reduces system performance or even makes it unstable [1].

A teleoperation system is essentially composed of the operator who is in contact with the master robot, the controllers for the control signals, communication channels and the slave robot which is in contact with the remote environment. The goal of teleoperation is to eliminate risks and allow the human operator to perform complicated missions and tasks in a remote or inaccessible environment [5]. Two essential aspects which characterize a bilateral teleoperation system: 1) stability: The slave faithfully reproduces the master's movements, 2) transparency: The operator feels the forces applied by the environment on the slave [5, 6]. However, these aspects are difficult to satisfy because of a number of problems such as the various dynamic uncertainties and nonlinearities in master-slave devices, the unavailability of an exact model that represents the operator's and the environment's behavior, the stability/transparency compromise, and also the inevitable problem of transmission delay in communication channels [6–8].

The transmission delay has a considerable influence on the behavior of the closed-loop system [7], because it can produce instabilities that are hard to correct and reduces the transparency of the entire system [8]. This dilemma constitutes a significant obstacle in the design of a controller guaranteeing stability and transparency simultaneously. Consequently, various efforts have been made in the literature on control laws and performance analysis of bilateral teleoperation systems with transmission delays.

For transparency, the four-channel control architecture proposed by Lawrence [9] is very efficient, but with presence of

the time delay in the communication channels, the stability cannot be guaranteed [8].
For stability, the wave variable method (WVM) based on the theory of passivity proposed by Niemeyer is generally used [10]. However, some traditional methods of wave variable can suffer from the effects of wave reflection and reduce the system's transparency performance. This has prompted several researchers to modify the architecture of this method in order to reduce these wave reflections [11], but obtaining good transparency performance is still difficult [12].
In order to solve the problem linked to the existence of transmission delays in bilateral teleoperation systems, several approaches have been proposed to deal with this problem such as predictive control [13], sliding mode control [14], optimal control [15], pole placement control [16] and the H∞ control [17]. However, these require precise knowledge of the dynamics of the system. For this reason, researchers have focused on artificial intelligence techniques and model-free control techniques.
The contribution of artificial intelligence with the concepts of neural networks (NNS), fuzzy logic (FL) and neuro-fuzzy networks makes it possible to remove several control constraints thanks to their structures, which adapt to changes in system state and input disturbances [18]. In recent years, intelligent controllers have become increasingly popular in the field of robotics and complex system control [19, 20]. (FL) uses human reasoning in the form of fuzzy rules to deal with imprecise concepts, is an appropriate approach for the control of complex systems [21]. (NNs) provide the ability to handle nonlinearities and complexities, offer adaptive adjustments and optimize the parameters of fuzzy controllers using a nonlinear learning algorithm such as backpropagation. By combining the interest of (FL) with the capabilities of (NNS), we can develop a neuro-fuzzy controller with improved features such as flexibility, adaptability and the ability to calculate data automatically and quickly.
Many works have been done in the literature using the neuro-fuzzy control, particularly the Adaptive Neuro-Fuzzy Inference System (ANFIS) in various areas notably in control engineering. For example, in the article [6], the authors used ANFIS to ensure the stability of the system in position-position control architecture for different constant transmission delays. In addition, ANFIS has been used in the control of teleoperation systems with dynamic uncertainties, which have given very good results [19, 21–24]].
To solve the problem of transmission delays in bilateral teleoperation systems, these artificial intelligence techniques are widely used alone or in combination with other control methods, for example in [12] and [25] the combination with the adaptive control is considered, the authors proposed an adaptive fuzzy backstepping control (AFBC) and a radial basis function (RBF) neural-network based adaptive control design, in order to reduce the influences of time delay and uncertain dynamics. Also in [26] and [27], two adaptive finite-time control schemes and an adaptive (NN) fixed-time control design are proposed for the problem of input saturation and time-varying delays respectively. On the other hand, we can also find artificial intelligence techniques in combination with the passivity concept. In [28] and [29], the (NN) based passivity control scheme and the type-2 fuzzy Takagi-Sugeno (T-S) model of the bilateral teleoperation system are designed. Recently, in [30] a passivity-based nonlinear controller was introduced for a bilateral teleoperation system under variable time delay and load disturbance. Another combination of artificial intelligence techniques with the impedance control method on the slave-side to control the contact force when the slave robot interacts with the remote environment has been used recently in [31] to improve the performance of the bilateral teleoperation system in the presence of time delay and force feedback.
The model-free schemes such as control with neural networks [32, 33] are widely used for system uncertainties and transmission delays. Thanks to the learning capabilities of neural networks, uncertainties can be estimated and improve performance.
Transmission delay, force feedback caused by the slave's contact with the remote environment, dynamic uncertainties, nonlinearities and external disturbances are the major constraints that affect the tracking performance of the bilateral teleoperation system. Therefore, the use of adaptive, robust and efficient controllers is very important. For this reason, the main contribution of this paper consists in the proposal of a controller based on artificial intelligence techniques in order to avoid the need of a precise model of the system. The importance is to prove the effectiveness of this approach experimentally on a Master/Slave experimental platform with one degree of freedom in force-position control architecture using the Arduino Due board and taking into account of transmission delay, force feedback and dynamic uncertainties (the dynamic models of the Master/Slave robots and that of the operator and the environment are unknown).
The rest of this paper is structured as follows: In section 2, the force-position control architecture with transmission time delay is presented. Section 3 presents the two controllers used (ANFIS) and (MWVM). Section 4 offers a brief overview of the Arduino Due board. Section 5 presents the experimental setup and the discussion of the experimental results obtained. Finally, a conclusion and an outlook on future directions of this research are given in section 6.

2. Transmission delay and force feedback

The problem of transmission delay in bilateral teleoperation systems was first raised by W.R. Ferrell in 1965 at NASA [34], where he highlighted the appearance of instability in delayed systems with force feedback, because the contacts and transmission delays in a closed-loop system create serious stability and control problems. Since then, overcoming this transmission problem has become the main control objective in bilateral teleoperation systems.

2.1 Bilateral teleoperation system

A bilateral teleoperation system is an exchange of two types of information, positions and forces between the master site which is manipulated by the human operator, and the slave site which is in contact with the remote environment [35]. The aim of force feedback is to provide to the user a sensation of presence in the remote environment by transmitting the force feedback information from the slave robot to the master robot through the communication channel (Fig. 1.)

2.2 Force-position control architecture

Fig. 2 shows the force-position control architecture in the presence of transmission delay used in this work. This is the most natural method to adopt for a force feedback, it requires the measurement of the interaction force between the slave robot and the environment by a force sensor [24, 35]. The master robot sends the position control signal to the slave robot, and the slave robot simultaneously returns the force contact signal to the master through the communication channel with transmission delay.

Where x_m, x_s represent the master and slave positions respectively. The x_{sd} defines the slave manipulator's desired position. The U_m, U_s reflect the master robot's command in force and the slave robot's command in position respectively. F_h, F_e denote the operator's force and the feedback force delivered to the master respectively. F_s denote the contact force provided by the environment to the slave robot. T_1, T_2: Transmission time delays.

Taking into account the communication channel with a constant time delay and $T_1 = T_2$, the signals will be delayed in time. For the control of the slave robot, it is the position of the master which is delayed in time, and for the control of the master robot it is the force feedback applied by the environment on the slave robot which is delayed, this is equivalent to write:

$$x_{sd} = x_m(t - T_1) \tag{1}$$

$$F_e = F_s(t - T_2) \tag{2}$$

The position error for the slave control and the force error for the master control are represented by means of the following:

$$e_s = x_{sd} - x - s = x - m(t - T_1) - x_s \tag{3}$$

$$e_m = F_e - F_h = F_s(t - T_2) - F_h \tag{4}$$

3. Adaptive neuro fuzzy inference system (ANFIS)

ANFIS is an adaptive hybrid combination of fuzzy inference system (FIS) with artificial neural network (ANN) [37]. It is one of the most used neuro-fuzzy algorithms in robotics and control of complex systems [18, 19, 21–23]. The ANFIS approaches integrates the best feature of neural networks with those of fuzzy systems in a single network [38]. Consequently, in the neuro-fuzzy system the membership functions of the FIS can be optimized and adjusted automatically using a learning algorithm of the ANN.

The ANFIS optimization approach is based on Takagi-Sugeno fuzzy inference systems, its architecture depends on two sets of training parameters: The parameters of the membership functions (premise) and the consequent parameters. ANFIS controller enhances properties such as flexibility, adaptability and the capacity to process data automatically [23], it adapts to changes, uncertainties and external disturbances by automatically adjusting the consequence parameters with the nonlinear learning algorithm based on extended Kalman filters, thus compensating for the unwanted effects of the transmission delay and maintain the system performance.

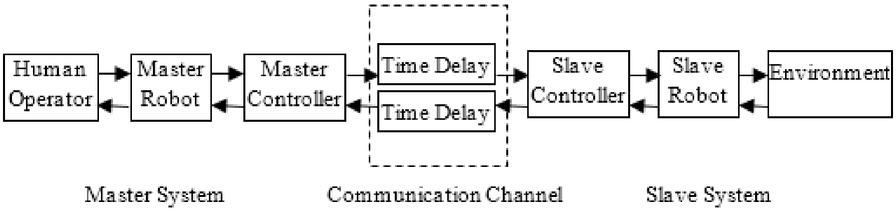

Figure 1. Block diagram of a bilateral teleoperation system.

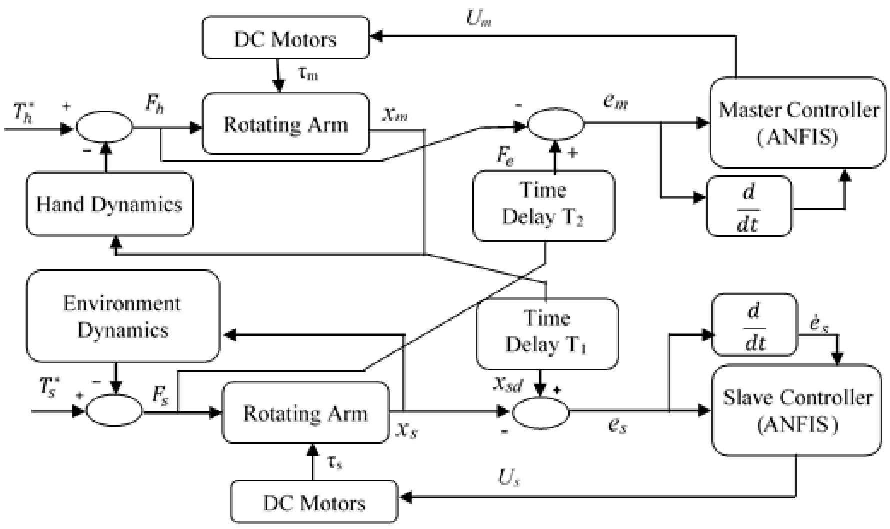

Figure 2. Architecture of force-position control with transmission delay.

In this work, two ANFIS controllers are developed, the first to control the slave robot in position and the second to control the master robot in force. To define the general structure of the ANFIS controller used in this work, considering the following system containing two inputs (x_1, x_2) and a single output u (Fig. 3).
Where x_1, x_2 are the error and it's derivative $[x_1, x_2] = [e, \Delta e]$.
For each input variable (error and error derivative), we associate two fuzzy sets namely N (Negative) and P (Positive) with membership degrees μ_N, μ_P respectively, defined by the following membership function, which are depicted in Fig. 4.
The value of L must be chosen by the manufacturer of the regulator; in this work we fixed it at 1 $(L = 1)$
For $i = 1, 2$

$$\mu_P(x_i) = \begin{cases} 0, & \text{if } x_i < -L \\ 0.5x_i + 0.5, & \text{if } -L < x_i < L \\ 1 & \text{if } .x_i > L \end{cases} \quad (5)$$

$$\mu_N(x_i) = \begin{cases} 1, & \text{if } x_i < -L \\ -0.5x_i + 0.5, & \text{if } -L < x_i < L \\ 0 & \text{if } .x_i > L \end{cases} \quad (6)$$

For each input, two fuzzy sets with four Takagi-Sugeno fuzzy rules are used. The fuzzy rules of the ANFIS controller in if -then of Takagi and Sugeno's form, can be written as follows:

$$\begin{cases} \text{Rule1 : if } x_1 \text{ is } A_1 \text{ and } x_2 \text{ is } B_1 \text{ then } f_1 = p_1x_1 + q_1x_2 + r_1 \\ \text{Rule2 : if } x_1 \text{ is } A_2 \text{ and } x_2 \text{ is } B_1 \text{ then } f_2 = p_2x_1 + q_2x_2 + r_2 \\ \text{Rule3 : if } x_1 \text{ is } A_1 \text{ and } x_2 \text{ is } B_2 \text{ then } f_3 = p_3x_1 + q_3x_2 + r_3 \\ \text{Rule4 : if } x_1 \text{ is } A_2 \text{ and } x_2 \text{ is } B_2 \text{ then } f_4 = p_4x_1 + q_4x_2 + r_4 \end{cases} \quad (7)$$

where: p_j, q_j, r_j are the consequence parameters of the rule j determined during the learning process by a learning algorithm. $A_{1,2}$, $B_{1,2}$ represent the fuzzy subsets.
Layer 1: Each node i of this layer represents a membership function, given as follows:

$$\begin{aligned} O_{1,j} &= \mu_{A_j} x_i \;\text{ for } j = 1,2 \\ O_{1,j} &= \mu_{B_{j-2}} x_i \;\text{ for } j = 3,4 \end{aligned} \quad (8)$$

Layer 2: Generates the appropriate degree of activation for the rule:

$$\begin{cases} w_1 = \mu_{A_1}(x_1) \cdot \mu_{B_1}(x_2) = \mu_p(x_1) \cdot \mu_p(x_2) \\ w_2 = \mu_{A_1}(x_1) \cdot \mu_{B_2}(x_2) = \mu_p(x_1) \cdot \mu_N(x_2) \\ w_3 = \mu_{A_2}(x_1) \cdot \mu_{B_1}(x_2) = \mu_N(x_1) \cdot \mu_p(x_2) \\ w_4 = \mu_{A_2}(x_1) \cdot \mu_{B_2}(x_2) = \mu_N(x_1) \cdot \mu_N(x_2) \end{cases} \quad (9)$$

Layer 3: Each node of this layer represents the normalized activation degree of the j^{th} rule

$$\overline{w_j} = \frac{w_j}{\sum_{j=1}^{4} w_j} \;\text{ for } j = 1,4 \quad (10)$$

Layer 4: Each node of this layer represents the normalized activation degree of the fuzzy rule f_j, by the following function:

$$\overline{w_j} f_j = \frac{w_j}{\sum_{j=1}^{4} w_j} f_j = \frac{w_j}{\sum_{j=1}^{4} w_j}(p_jx_1 + q_jx_2 + r_j) \quad (11)$$

Layer 5: This layer is the sum of all incoming signals

$$u = \sum_{j=1}^{4} \overline{w_j} f_j = \frac{\sum_{j=1}^{4} w_j f_j}{\sum_{j=1}^{4} w_j} \quad (12)$$

3.1 Learning algorithm and stability analysis of ANFIS control

This learning algorithm is used to identify and adjust the parameters of ANFIS regulators in real time and simultaneously with the operation of the system. During the learning process, the behavior of the network is modified iteratively until the desired behavior is achieved. Here, the same learning algorithm is developed for each ANFIS controller, such that $(k = s)$ for the first ANFIS controller which controls slave robot in position, and $(k = m)$ for the second ANFIS controller which commands the master robot in force.
This algorithm allows for the adjustment of the premises and consequence parameters by minimizing the following objective function [21]:

$$J = \frac{1}{2}(y_d^k - y^k)^2 \quad (13)$$

where y_d is the desired output, and y is the actual output of the system to be controlled.

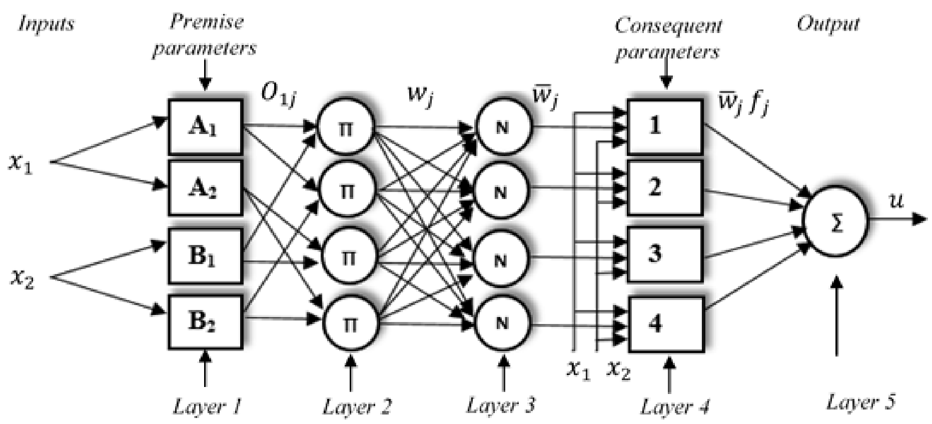

Figure 3. ANFIS Controller Architecture [36].

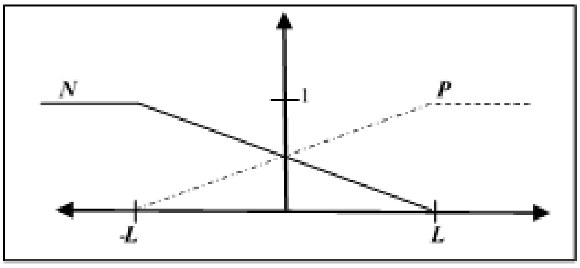

Figure 4. Membership functions of master and slave devices [6].

Let be: ϕ_j^k the vector of parameters to adjust which are (p_j, q_j, r_j).
In order to obtain these parameters, we use the gradient descent method [39] as follows:

$$\phi_j^k(k+1) = \phi_j^k(k) - \beta(k)\frac{\partial J}{\partial \phi_j^k} \tag{14}$$

We have:

$$\frac{\partial J}{\partial \phi_j^k} = \frac{\partial J}{\partial u^k}\frac{\partial u^k}{\partial \phi_j^k} = -(y_d^k - y^k)\frac{\partial y^k}{\partial u^k}\frac{\partial u^k}{\partial \phi_j^k} \tag{15}$$

$$\text{Let be : } e^k = y_d^k - y^k \tag{16}$$

From (15) and (16):

$$\frac{\partial J}{\partial \phi_j^k} = -\frac{\partial y^k}{\partial u^k}\frac{\partial u^k}{\partial \phi_j^k}e^k \tag{17}$$

From equations (14) and (17), it follows:

$$\phi_j^k(k+1) = \phi_j^k(k) + \beta(k)\frac{\partial y^k}{\partial u^k}\frac{\partial u^k}{\partial \phi_j^k}e^k \tag{18}$$

$\partial y^k/\partial u^k$ cannot be evaluated. However, we may estimate it using the extended Kalman filter formulae [40].
Equation (18) can be written as:

$$\phi_j^k(k+1) = \phi_j^k(k) + k_j^k(\Psi_j^k)^T e^k \tag{19}$$

where:

$$(\Psi_j^k)^T = \frac{\partial u^k}{\partial \phi_j^k} = \left[\frac{\partial u^k}{\partial p_j^k}\ \frac{\partial u^k}{\partial q_j^k}\ \frac{\partial u^k}{\partial r_j^k}\right] \tag{20}$$

$$k_j^k = \beta(k)\frac{\partial y^k}{\partial u^k} \tag{21}$$

Equation (19) is an extended Kalman filter equation [40]

$$\phi_j^k(k+1) = \phi_j^k(k) + H(k)e^k \tag{22}$$

where $H(t)$ is the Kalman gain defined as follow:

$$H(k) = \frac{y_1}{(\Psi_j^k)y_1(\Psi_j^k)^T + y_2}(\Psi_j^k)^T \tag{23}$$

y_1, y_2: Adaptation gains to vary the speed of convergence.
Equation (22) can be written as:

$$\phi_j^k(k+1) = \phi_j^k(k) + \frac{y_1}{(\Psi_j^k)y_1(\Psi_j^k)^T + y_2}(\Psi_j^k)^T e^k \tag{24}$$

By identification between equation (19) and (24):

$$k_j^k = \frac{y_1}{(\Psi_j^k)y_1(\Psi_j^k)^T + y_2} \tag{25}$$

Consequently, ϕ_j^k can be estimated by the following:

$$\phi_j^k(k+1) = \phi_j^k(k) + k_j^k(\Psi_j^k)^T e^k \tag{26}$$

For a very short sampling time T_e:

$$\dot{\phi}_j^k = \frac{\phi_j^k(k+1) - \phi_j^k(k)}{T_e} = \frac{k_j^k}{T_e}(\Psi_j^k)^T e^k = (\Psi_j^k)^T e_u^k \tag{27}$$

where:

$$k_1^k = \frac{k_j^k}{T_e}$$

$$e_u^k = k_1^k e^k$$

Let be $\widetilde{\phi}_j^k = \phi_{jd}^k - \phi_j^k$, where ϕ_{jd}^k is the vector of the desired parameters and ϕ_j^k is the vector of the actual parameters.
That implies:

$$\dot{\widetilde{\phi}}_j^k = \dot{\phi}_{jd}^k - \dot{\phi}_j^k = -(\Psi_j^k)^T e_u^k \tag{28}$$

where $e_u^k = u_d - u$: The error between the controller's desired output and the actual output. For linear variation, it is defined by:

$$\begin{aligned} e_u^k &= \sum_{j=1}^{4}[(\Psi_j^k)\phi_{jd}^k - (\Psi_j^k)\phi_j^k] \sum_{j=1}^{4}[(\Psi_j^k)(\phi_{jd}^k - \phi_j^k)] \\ &= \sum_{j=1}^{4}[(\Psi_j^k)\widetilde{\phi}_j^k] \end{aligned} \tag{29}$$

For analysis of control system stability, we consider the following Lyapunov function [41]

$$V_j^k = \frac{1}{2}\sum_{j=1}^{4}\left((\widetilde{\phi}_j^k)^T(\widetilde{\phi}_j^k)\right) \tag{30}$$

$$\dot{V}_j^k = \sum_{j=1}^{4}\left((\dot{\widetilde{\phi}}_j^k)^T(\widetilde{\phi}_j^k)\right) \tag{31}$$

From (28) and (31):

$$\dot{V}_j^k = \sum_{j=1}^{4}\left((-(\Psi_j^k)^T e_u^k)^T(\widetilde{\phi}_j^k)\right) \tag{32}$$

$$\dot{V}_j^k = -(e_u^k)^T\sum_{j=1}^{4}\left((\Psi_j)^k(\widetilde{\phi}_j^k)\right) \tag{33}$$

Using (29) and (33):

$$\dot{V}_j^k = -(e_u^k)^T e_u^k \leq 0 \tag{34}$$

From (34), $\dot{V}_j^k \leq 0$, according to the LaSalle theorem, the system is asymptotically stable in the sense of Lyapunov.
To prove the effectiveness of the designed controllers ANFIS, it is necessary to compare their performances with a

more recent control method for controlling bilateral teleoperation systems with transmission delay. The wave variable method proposed by Niemeyer and Slotine in [10] suffers from wave reflection, but the modified wave variable method (MWVM) proposed in [11] has been used in several recent works [8, 42] and has proven its effectiveness. For this, in this paper, we made a comparison between the experimental results that we found by the ANFIS controllers and those that we found by the conventional PI regulator associated with the modified wave variable method (PI+MWVM) for the case of control with transmission delay and force feedback.

3.2 The modified wave variable method (MWVM)

The wave variable method presents a modification and extension of the passivity theory; The aim is to minimize the negative effects of transmission delays in control of bilateral teleoperations systems. However, wave reflection of traditional (WVM) leads to disturbances and unpredictable disorders that can destabilize the entire system. For this, L. Bate et al. in [11] have implemented the modified wave variable method (MWVM) to reduce the waves reflection for unknown environments (Fig. 5).

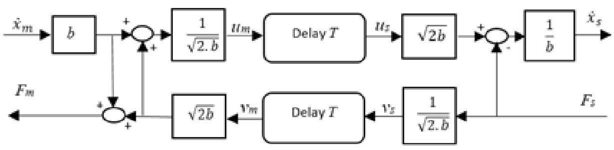

Figure 5. Modified Wave Variable Method (MWVM) block diagram [11].

Where b is the characteristic impedance, also known as wave impedance, can be a positive constant or a positive definite symmetric matrix, the variation of the value of b influences the behavior and performance of the system. u represents the wave going from the master robot to the slave robot, while v represents the wave returning from the slave to the master. T represents the time delay.
From the structure shown in Fig. 5, the equations can be deduced as follows:

$$u_s(t) = u_m(t-T) \tag{35}$$

$$v_m(t) = v_s(t-T) \tag{36}$$

$$u_m(t) = \frac{\dot{b}x_m(t) + F_s(t-T0}{\sqrt{2b}} \tag{37}$$

$$v_s(t) = \frac{F_s(t)}{\sqrt{2b}} \tag{38}$$

$$\dot{x}_s(t) = \dot{x}_m(t-T) + \frac{1}{b}(F_s(t-2T) - F - s(t)) \tag{39}$$

$$F_m(t) = F_s(t-T) + b\dot{x}_m(t) \tag{40}$$

To ensure a high control rate and obtain good system performance, it is necessary to choose the right hardware to use. Given its remarkable features and capabilities, the Arduino Due board was chosen for this project.

4. Arduino Due board

This board was released in October 2012 [43], and it is the first Arduino board to use a 32-bit ARM core microprocessor with a significant variety of inputs/outputs [44]. The clock frequency of 84 MHz enables complex calculations to be performed in a very short time. Heavy programs have sufficient memory capacity [45], instead of the usual 8-bit resolution (Analog Write (0...255)), the 12 digital pins on the Arduino Due board have an extended resolution to 12 bits (Analog Write (0...4095)) [45]. Arduino Due is the most powerful and fastest board in the Arduino range, ideal for projects requiring high performance, reason why it was chosen for this project. The Arduino Due Board shown in Fig. 6 is equipped with an ARM Cortex-M3 SAM3X8E processor from Atmel. It contains 54 digital I/O with the possibility of using 12 outputs as PWM, 12 analog inputs, 4 UART hardware serial ports, USB OTG compatible connection, 2 DACs, 2 TWI, a power jack, a SPI header, a JTAG header, a reset button and a clear button. The Arduino Due microcontroller operates over a voltage range of $7-12$ V thanks to its on-board voltage regulator. The microprocessor operates with a voltage of 3.3 V. The microcontroller consumes in normal operation, up to 70 mA (if it does not supply anything) and can accept a maximum current of $3-15$ mA on each IO pin. The input/output ports of this Arduino Due board are designed to receive voltages of 3.3

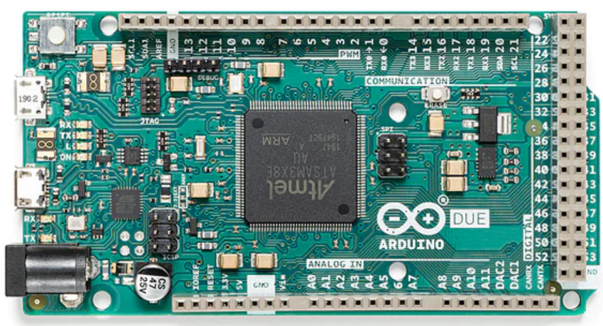

Figure 6. The Arduino Due Board.

V.

5. Experiment

5.1 Experimental setup

In this work, the two neuro-fuzzy controllers ANFIS for the force - position control architecture are developed in the Matlab/Simulink environment. Fig. 7 and Fig. 8 illustrate the experimental platform and the Synoptic of our bilateral teleoperation system. It consists of two identical direct current motors DC 12 V 184 p (Gear motor with encoder–DF Robot) which forms the master-slave assembly, each motor is equipped with an encoder to indicate the value of its angular position. To measure the interaction forces of the operator on the master side and the environment on the slave side, we equipped each robot with a rotating arm equipped with a 120 Ω strain gauge. These gauges make it possible to measure the mechanical deformation and deduce the force applied using a wheatstone bridge in 1/4 configuration and

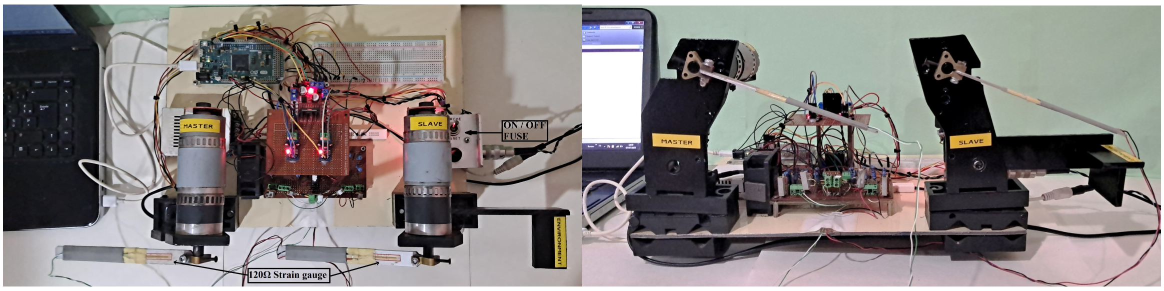

Figure 7. Our experimental platform of bilateral teleoperation system with transmission time delay [6].

an INA126p instrumentation amplifier. To measure the master and slave motor torques, we placed two ACS 712 current sensors for each motor.
The Arduino Due board used in this project allows us to acquire all the signals mentioned above (position, force, torque) and transfer them to Matlab/Simulink which is equipped with specific packages (MATLAB and Simulink Support Package for Arduino Hardware). The direction of rotation of the two motors is controlled via the drivers L198N.
To prove the efficiency and adaptability of the two neuro-fuzzy controllers ANFIS designed in this work with the aim of guaranteeing and improving the stability and transparency of a nonlinear, bilateral teleoperation system with transmission time delay and force feedback (the models of the master/slave robots and that of the human/environment are unknown), a series of experiments with three types of controllers to make the comparison are carried out:

C1: The conventional PI controller with the parameters in Table 1 (which we found using the PID Tuner tool in the Matlab environment).

C2: The same PI controller with the modified wave-variable methode (PI+MWVM) proposed by L. Bate in [11], the wave impedance (b) is chosen as $b = 4$.

C3: The ANFIS controllers designed in this work.

Table 1. Parameters of PI controllers.

Parameters	Value
K_P	22.4
K_I	0.32

These controllers are studied in three different situations:
Situation (I): Without transmission delays, in free movement (no obstacle: without force feedback).
Situation (II): With transmission delay, in free movement (no obstacle: without force feedback).
Situation (III): With transmission delay and in contact with a hard obstacle (with force feedback).

5.2 Experimental results

The aim of these experiments is to compare the three control modes under the same working conditions, in order to have a conclusion on which controller will allow us to obtain good position and torque tracking in the presence of constraints such as dynamic uncertainties, nonlinearities of master-slave devices, transmission delay and force feedback, while ensuring system performance in terms of stability, transparency and speed.

Situation (I): Without transmission delay and in free movement (no obstacle: Without force feedback)

The experimental results in Figs. 9 (a, b, c, d) and Figs. 10 (a, b, c, d) show the position tracking, the torque, the operator's force applied on the master robot, and the position error

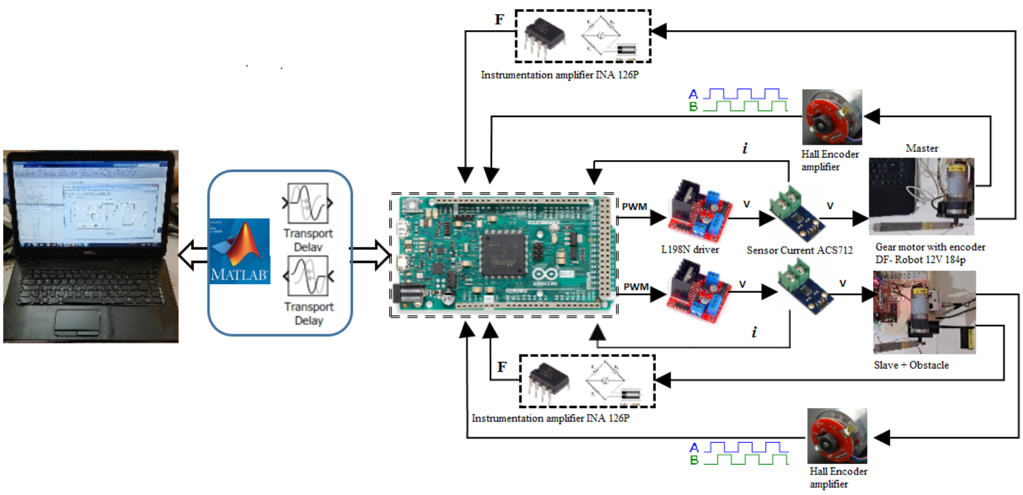

Figure 8. Synoptic of the experimental platform.

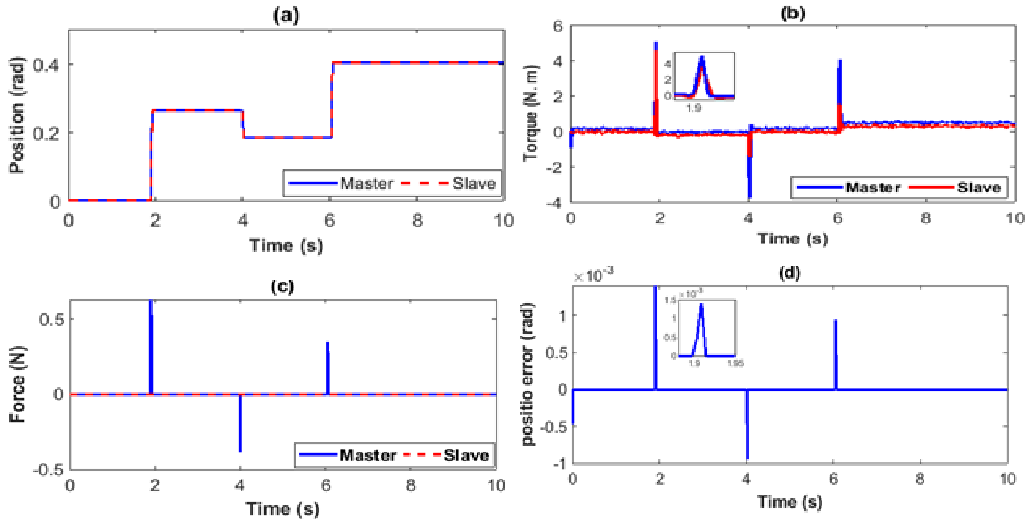

Figure 9. ANFIS Control without time delay and no obstacle ((a): Master and slave position tracking, (b): The Torque, (c): Human force exerted on the master robot, (d): Position error).

obtained by control with the ANFIS and PI controllers respectively.
The Root Mean Square Errors (RMSE) of position and torque tracking errors (Master–Slave) in Fig. 9 and Fig. 10 are listed in Table 2.
(RMSE) can be represented as:

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}(\sum_{i}^{N} y_{mi} - y_{si})^2} \tag{41}$$

where y_{mi} and y_{si} represents position or torque of master robot and the slave robot respectively, $i = 1, \ldots, N$.
N represents the number of sample value.
In this situation (I), the results show a good position and torque tracking with both controllers ANFIS and PI, the position errors obtained are very acceptable. These results prove that the parameters of the two regulators ANFIS and PI are very well chosen.

Table 2. RMSE (tracking errors for Fig. 9, Fig. 10).

Controller	Position (rad)	Torque (Nm)
ANFIS	0.000800	0.0980
PI	0.000561	0.0937

Situation (II): With transmission delay and in free movement (no obstacle: Without force feedback)

The experimental results in Figs. 11 (a, b, c, d) and Figs. 12 (a, b, c, d) show the position tracking, the torque, the force applied by the operator on the master robot, and the position error by ANFIS and PI controllers respectively, in presence of a constant transmission delay of $T_1 = T_2 = 300$ ms. The Root Mean Square Errors (RMSEs) of position and torque tracking errors (Master–Slave) in Fig. 11 and Fig. 12 are listed in Table 3.

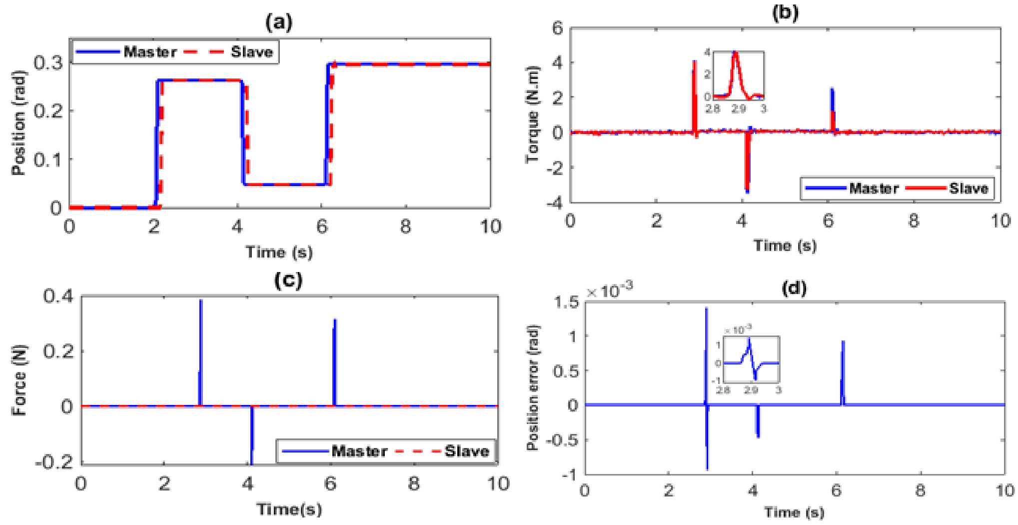

Figure 10. PI Control without time delay and no obstacle ((a): Master and slave position tracking, (b): The Torque, (c): Human force exerted on the master robot, (d): Position error).

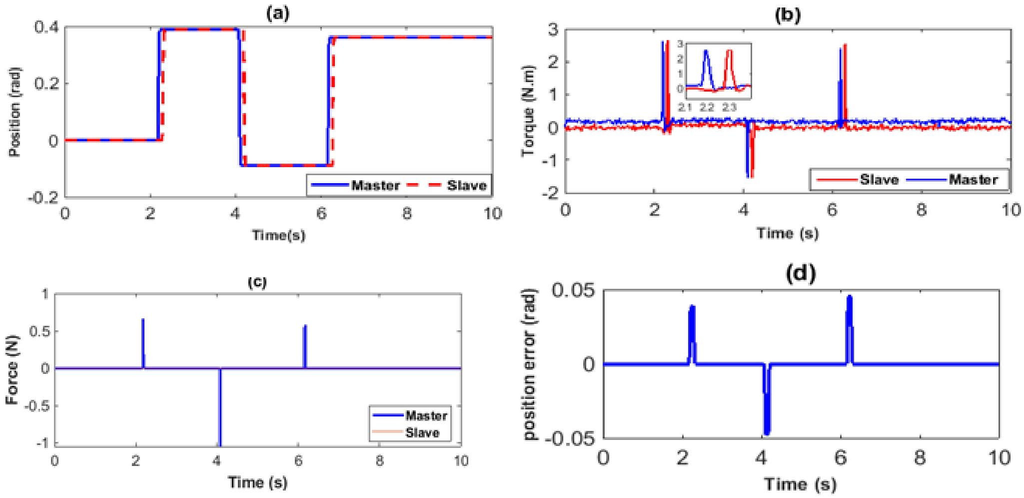

Figure 11. ANFIS Control with constant time delay ($T_1 = T_2 = 300$ ms), no obstacle ((a): Master and slave position tracking, (b): The Torque, (c): Human force exerted on the master robot, (d): Position error).

In this situation (II), even though the position curves show very good position tracking by both controllers ANFIS and PI, but the torque curves distinguish between these two controllers, because the torque curves obtained by the ANFIS controllers are clearly better than those obtained by the PI controller. These results prove that the two motors master and slave, rotate at the same speed despite the presence of the transmission delay, and also show the automatic adaptability and precision of the ANFIS controllers compared to the PI controllers.

Table 3. RMSE (tracking errors for Fig. 11, Fig. 12).

Controller	Position (rad)	Torque (Nm)
ANFIS	0.0300	0.3069
PI	0.0381	0.5108

Situation (III): With transmission delay and in contact with a hard obstacle (with force feedback)

In this situation, a hard contact (obstacle) is introduced in interaction with the slave robot, which creates a force feedback in the closed-loop of the bilateral teleoperation system with constant transmission delay. The aim of this experiment is to verify the ability of the slave manipulator to recover position tracking after contact with a hard obstacle. In this situation (III), the experiment is carried out for all three types of controller (C1, C2 and C3). The Root Mean Square Errors (RMSEs) of position and torque tracking errors (Master – Slave) in Fig. 13, Fig. 14 and Fig. 15 are listed in Table 4.

1) Experimental results with C1 control in situation (III) The experimental results in Figs. 13 (a, b) show the position and torque curves for control with the C1 controller in the presence of a constant transmission delay $T_1 = T_2 = 300$ ms and in interaction with a hard obstacle.

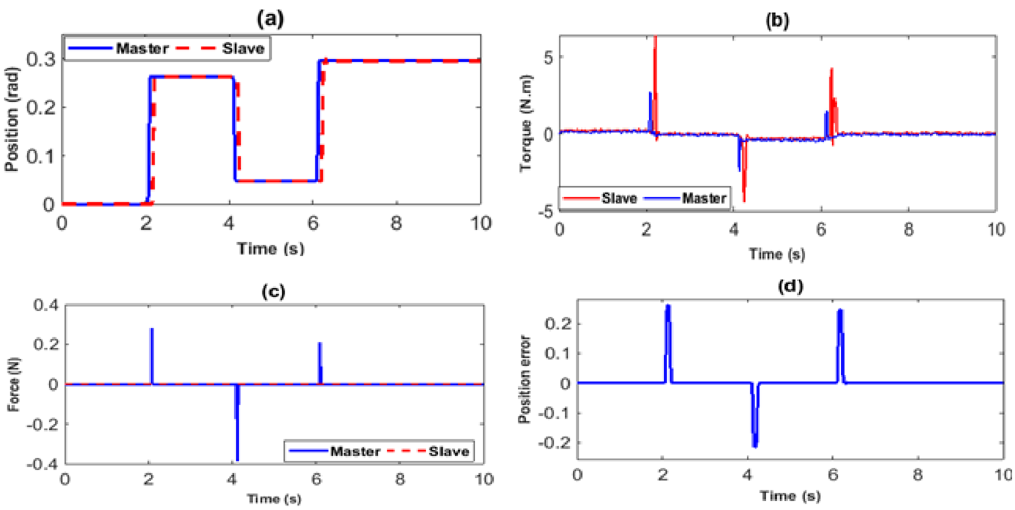

Figure 12. PI Control with constant time delay ($T_1 = T_2 = 300$ ms) and no obstacle ((a): Master and slave position tracking, (b): The Torque, (c): Human force exerted on the master robot, (d): Position error).

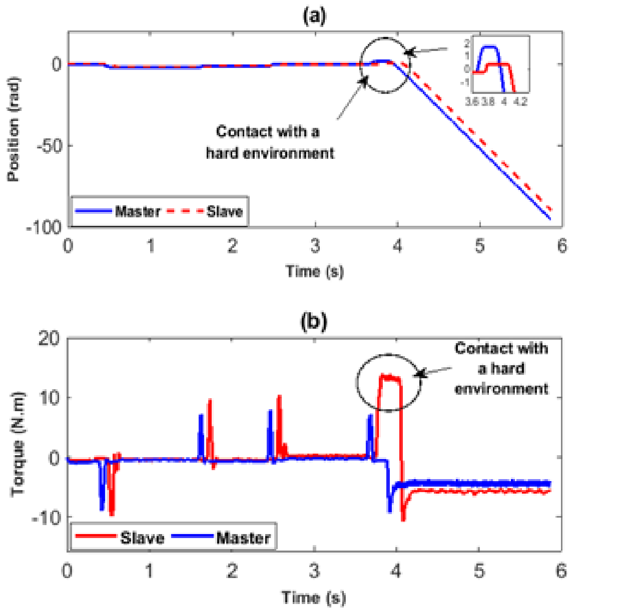

Figure 13. PI Control with constant time delay ($T_1 = T_2 = 300$ ms) and contact with a hard environment ((a): Master and slave position tracking, (b): The Torque).

This curves show that before interaction with a hard obstacle, a good position and torque tracking of the master and slave robots is obtained, but as soon as the slave robot interacts with the a hard obstacle at instant $t = 3.8$ s, the system diverges completely and becomes unstable. This proves that the PI controller alone cannot ensure the stability of the bilateral teleoperation system in the presence of transmission delay and force feedback. For this, in the following experiment we introduce the modified wave variables method.

1) Experimental results with C2 control in situation (III) To try to overcome the stability problem of the previous case, the modified wave variable method is introduced (PI+MWVM) in this experiment, under the same conditions (the same PI controller, the same transmisson time delay and in contact with the same hard obstacle). The experimental results are shown in Figs. 14 (a,b).

This curves, show that the slave comes into contact with the hard obstacle at $t = 4.4$ s and that the system does not diverge. Due to the reduction in the wave reflection problem, the operator may feel the collision, but he may feel greater force feedback from the slave, which may damage the equipment. At $t = 4.9$ s, when the obstacle is removed, the slave tries to resume tracking of the master, but it barely manages to resume, and the fluctuations and oscillations remain continuous, which considerably reduces the system performance.

1) Experimental results with C3 control in situation (III) In this case, we control our bilateral teleoperation system with transmission delay and force feedback by ANFIS designed controllers, for the same transmission delay and the same hard obstacle which will be introduced in interaction with the slave robot twice in succession, the behavior of the system during and after each release of the obstacle is shown in Fig. 15.

The aim of this experiment is that the operator must feel the forces applied by the obstacle on the slave robot (transparency), the slave resumes position tracking just after the obstacle is released, and the whole system master-slave remains stable.

The experimental results in Figs. 15 (a, b, c) clearly show that the slave robot interacts with a hard obstacle twice, the first time at ($t = 3.6$ s) and the second time at ($t = 6.5$ s). Two key points emerge from the analysis of these results: The first is that at each contact with an obstacle, the human operator feels the effect of the collision, so the master robot turns back in proportion to the force of the interaction which is subject to the transmission delay. The second point is that after each release of the obstacle, the slave quickly and perfectly resumes its master's position following trajectory. These two observations confirm the transparency between the two sites (master-slave) and the stability of the closed-loop system.

This experimental study has demonstrated the robustness and capacity of the two ANFIS controllers designed to achieve the performance of bilateral teleoperation system with transmission delays and in contact twice in a row with a hard obstacle which creates a force feedback.

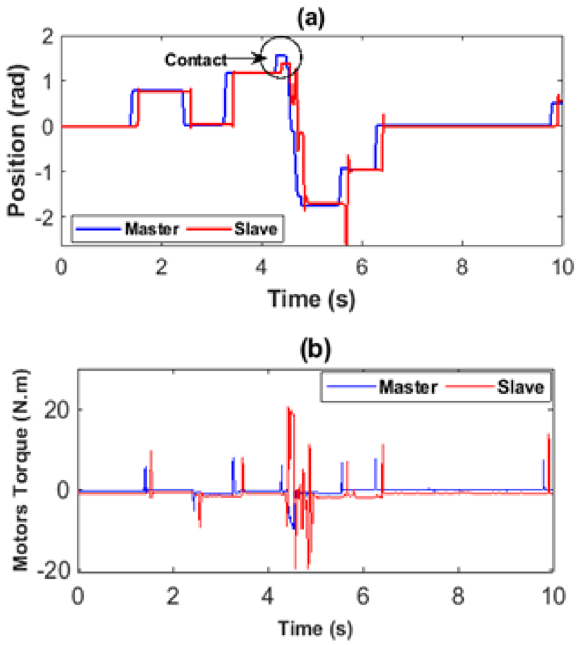

Figure 14. (PI+MWVM) Control with constant time delay ($T_1 = T_2 = 300$ ms) and contact with a hard environment ((a) Master and slave position tracking, (b): The Torque).

Table 4. RMSE (tracking errors for Fig. 13, Fig. 14, Fig. 15).

Controller	Position (rad)	Torque (Nm)
PI	3.3588	4.1210
PI+MWVM	0.3470	3.4771
ANFIS	0.3284	2.1862

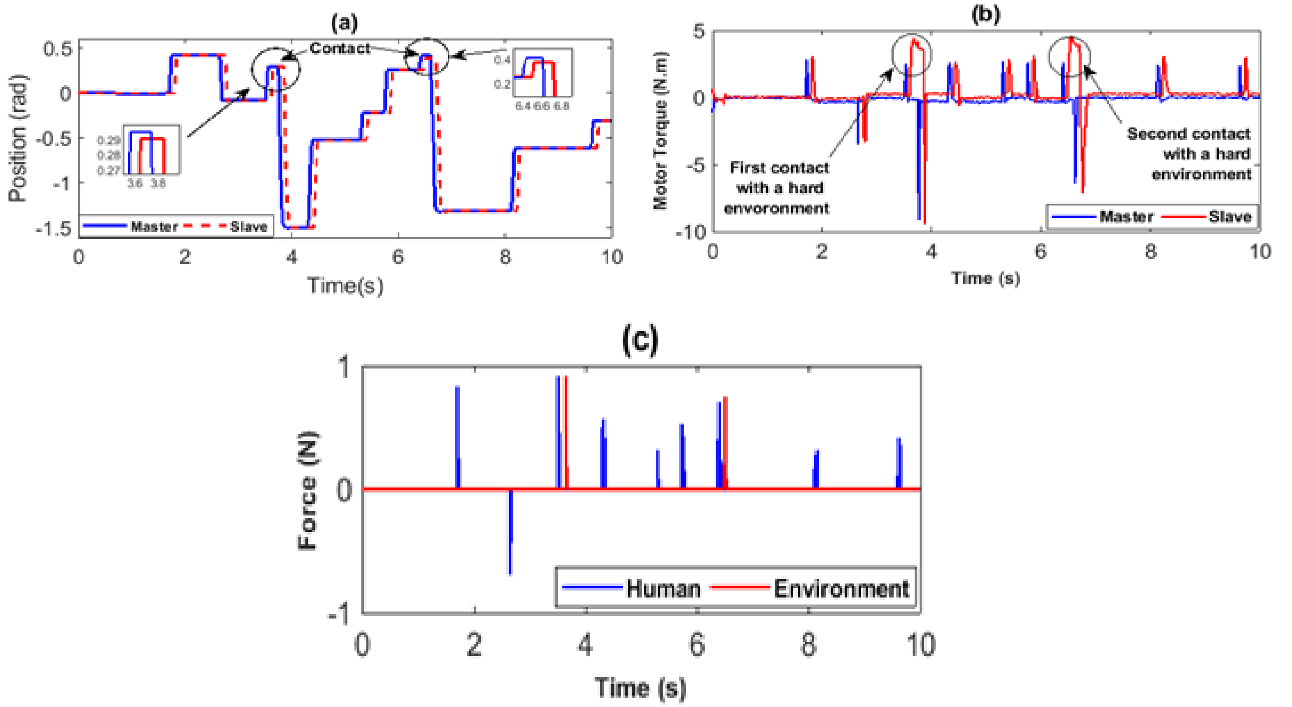

Figure 15. ANFIS Control with constant time delay ($T_1 = T_2 = 300$) ms and contact with a hard environment ((a): Master and slave position tracking, (b): The Torque, (c): human and environment force applied to the master and slave robots respectively).

To test the effectiveness of the proposed approach under the influence of disturbances and modeling variations with transmission delay, we added in this work three additional experiments: The first consists in adding an impulse disturbance of amplitude of 0.9 (Nm) at time $t = 3.6$ s and the second consists in adding a step disturbance of amplitude of 1 (Nm) at time $t = 3.5$ s, and in the third experiment we replaced the two direct current motors DC 12 V 184 p (Gear motor with encoder–DF Robot) with two other DC motors (Gear motor with encoder JGA 25-370). The transmission delay is the same as the previous experiments.

Fig. 16 and Fig. 17 show the behavior of the system with the ANFIS controllers in presence of transmission delays and external disturbances. Fig. 18 shows the position and torque tracking with the two new motors (JGA 25-370) in the presence of the same transmission delay.

These experimental results demonstrate the ability of the two designed ANFIS controllers to adapt to variations and unexpected disturbances in the system, thus ensuring the performance (tracking, transparency and stability) of a bilateral teleoperation system with transmission delays. This is due to the adaptability of the ANFIS controller and its error compensation capability using a learning algorithm based on the extended Kalman filter.

6. Conclusion

In this article, considering the communication time delay, force feedback, dynamic uncertainties, and various nonlinearities in bilateral teleoperation systems, an adaptive neuro-fuzzy control design has been proposed to achieve simultaneous stability and good transparency performance. Implemented in the Matlab/Simulink environment for a force - position control architecture, using the Arduino Due board which benefits from its computational speed and power. Thanks to the learning algorithm that quickly and automatically adjusts the parameters of the premises

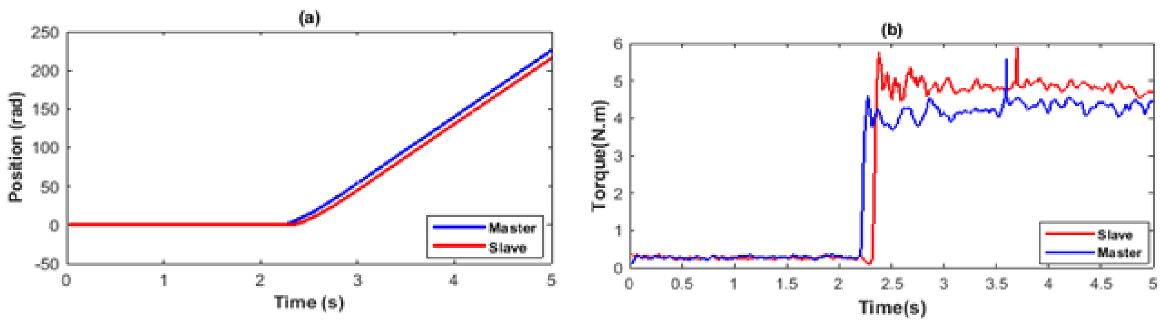

Figure 16. ANFIS control in the presence of an impulse disturbance and constant transmission delay ((a): Master and slave position tracking, (b): Torque tracking).

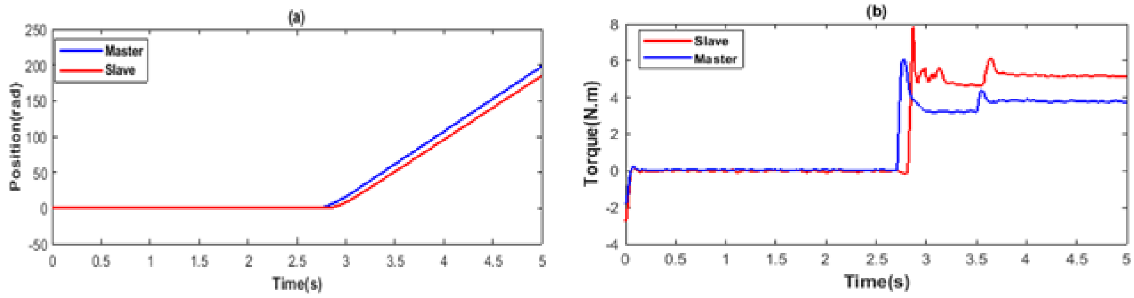

Figure 17. ANFIS control in the presence of a step disturbance and constant transmission delay ((a): Master and slave position tracking, (b): Torque tracking).

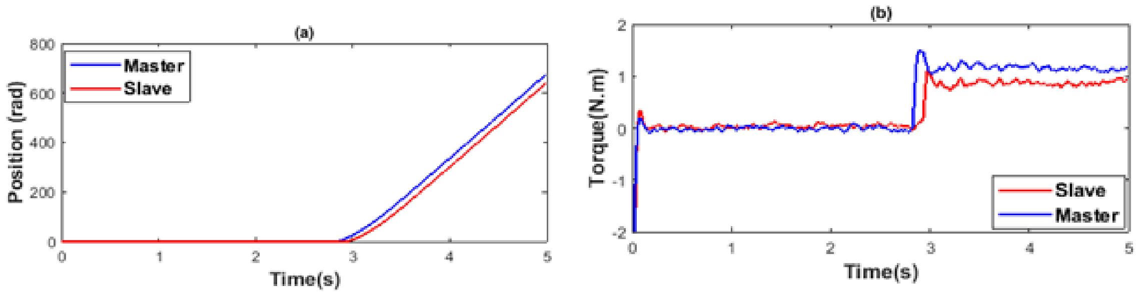

Figure 18. ANFIS control for the new model (JGA25-370) in the presence of constant transmission delay ((a): Master and slave position tracking, (b): The Torque tracking).

and consequences of the neuro-fuzzy network, and the combination of the advantages of fuzzy logic with those of neural networks, ANFIS controllers have experimentally proven their ability to compensate for the undesirable effects of transmission delay and force feedback and they guaranteed the performances of the system with excellence despite the presence of various constraints such as dynamic uncertainties, disturbances and nonlinearities of the system. The good choice of equipment used in our experimental platform allowed us to achieve very good practical results. We are considering future work on this platform that will take into account the variable transmission delays and disturbances using the ANFIS controller equipped with an intelligent compensation method.

Authors contributions
Authors have contributed equally in preparing and writing the manuscript.

Availability of data and materials
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflict of interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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