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Design and Implementation of Adaptive Neuro-fuzzy Exergame Controller

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Original Article

Abstract

Introduction: Due to sedentary postures caused by video games, many health-related issues have occurred among players. One practical solution for dealing with the aforementioned problem is to come up with game controllers which promote physical exercises. In this study, an adaptive neuro-fuzzy exergame controller was introduced.

Materials and Methods: During the training stage, the parameters of the fuzzy logic's member functions were fine-tuned. By calculating a gradient vector and by applying backpropagation, the aforementioned parameters were updated using the measured error. The controller was made of four pads, each containing a resistor and a pushbutton, which were connected to a microcontroller. In order to improve the user experience, an adaptive neuro-fuzzy logic system was used to analyze the gathered data from the controller.

Results: A pure fuzzy logic system (FLS) cannot provide an acceptable playing experience for players of different ages and physical characteristics. The received signal from the controller was sent to a fine-tuned FLS. The calculated output of the previously trained FLS was one of the defined classes of "ignore", "press", and "hold", which was sent as a command to the main computer.

Conclusion: In the proposed method, the FLS was fine-tuned by gathering data from the user, which improved the performance of the controller due to the fact that the controller was trained to best suit the needs of the user. The gathered data was then used to change the parameters of the FLS to provide an acceptable playing experience for the user.

Keywords: Serious games; Training; Sight reading; Gamification; E-learning

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Introduction

Video games take up a large part of adolescents' leisure time and make them immobile (1). Therefore, in order to solve this problem, the application of new technologies in the development of exergames for a wide range of users seems necessary. Exergames are video games that involve physical activity. These games can easily solve many of the problems caused by long-term use of video games (2).

In addition, exergames are able to motivate individuals of different ages and interests to maintain them healthy (3,4).

An integral part of exergames is the controller used in these games. These controllers range from pushbuttons to more advanced equipment such as Kinect and PlayStation Move (5). There is a long history behind various ideas for controlling exergames (6). In 1983, Autodesk introduced the High Cycle bicycle. The user of this device must pedal fast enough to be able to fly over the virtual environment of the game (7). In 1998, Konami

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introduced the Dance Dance Revolution game. The controller used in this game receives user commands via push switches (8). The above examples are simple yet innovative samples of controllers. A more complex example of such a controller is the Kinect, which was launched in 2010 and led to major advances in user motion detection. The Kinect system uses an infrared projector, a camera, and a microchip to determine the position of an object in three dimensions. In recent years, virtual reality (VR) has been widely used in the development of exergames as well as the training of professional athletes (9,10). All of the above examples highlight the importance of developing exergames controllers. Another basic point is that exergames can be used in various public places, including subway stations, malls, etc., to improve the physical health of individuals of different tastes and ages (11). Moreover, these games are an important part of rehabilitation therapy games that help specialists and patients achieve simple to complex motor goals over time. In order to make the best use of domain knowledge or data collected from an expert, a fuzzy system can be implemented. The present study is conducted with the aim to design and implement an adaptive neuro-fuzzy controller for exergames.

Materials and Methods

Fuzzy system: The most important part of a fuzzy system is its database, which consists of fuzzy rules (12). These rules are if-then fuzzy statements that describe the general behavior of a fuzzy system. The fuzzy inference system (FIS) is then used to map the input space $U \in R^n$ to the output space $V \in R$. The inputs of a fuzzy system (and sometimes its output) are fuzzy sets with their own membership functions. In short, it can be stated that the fuzzy system provides a nonlinear mapping of the database. Fuzzy set A with a continuous membership function is represented as Equation 1.

$$A = \int_U \mu_A(x)/x \qquad \text{Equation 1}$$

The integral sign actually denotes a set of all points $x \in U$ the membership function of which is $\mu_A(x)$ (12). In fact, the task of a membership function is to nonfuzzify a fuzzy concept (13). The membership functions are determined using the domain knowledge or experience of an expert. In the proposed method, the membership functions were defined in such a way to be usable by a wide range of users. In this method, when setting the controller, the data collected from the user were used to determine the appropriate parameters for the membership functions. Reasoning in a fuzzy system means obtaining new statements using previous statements (14). Unlike classical logic, which is a two-value logic, the fuzzy system allows the statements to take any value in the interval [0, 1]. This plays an important role in facilitating the approximate reasoning process. The statements are expressed by fuzzy sets and some basic concepts are introduced in order to achieve approximate reasoning (12,14).

The generalized modus ponens inference (15) states that having two fuzzy propositions $IF\ x\ is\ A\ THEN\ y\ is\ B$ and $x\ is\ A'$, the new fuzzy proposition $y\ is\ B'$ is concluded as the closer A' is to A, B' will also be closer to B. With the fuzzy set A' and the relation $A \rightarrow B$ in space $U \times V$, which expresses the fuzzy proposition $IF\ x\ is\ A\ THEN\ y\ is\ B$, the fuzzy set B' is concluded as relation 2.

$$\mu_{B'}(y) = \sup_{x \in U} t(\mu_{A'}(x), \mu_{A \rightarrow B}(x, y)) \qquad \text{Relation 2}$$

Where t represents t-norm. In fact, fuzzy inference is the method of reaching from a given input to an output using fuzzy rules. In the proposed method, Sugeno type fuzzy inference system was employed. In this method, Singleton membership functions are used for the system output, which is either a fixed value or a linear function of the input. The nonfuzzification process is computationally cost-effective as it uses a weighted average or a weighted sum of a limited amount of data (16). The system output can be displayed using Equation 3.

$$\text{Output} = \frac{\sum_{i=1}^{N} w_i z_i}{\sum_{i=1}^{N} w_i} \qquad \text{Relation 3}$$

Where N, W_i, and Z_i are the number of rules, the rule firepower, and the rule output level, respectively. As mentioned earlier, Z_i can be a fixed value or a linear function of input (17).

Adaptive Neuro-fuzzy Inference System (ANFIS): An essential step in the controller design was the collection of data from the user to create a dataset to adjust the fuzzy system parameters (18). As mentioned earlier, the designed system was used by users with different physical characteristics. Therefore, it was necessary to change the designed system according to the needs of each user. The parameters of the system membership functions could be changed using the adaptive neuro-fuzzy system (19). The adjustment of the afore-mentioned parameters was possible by calculating the gradient vector as a criterion for determining the quality of modeling the input and output of the system for a number of parameters.

In the training phase, the parameters of the membership functions were changed using the training data set used to train the current model. Using the gradient vector calculated, the parameters of the fuzzy system were updated using the backpropagation method (18) and based on the calculated error (sum of the differences between the actual output and the desired output). In fact, the calculated gradient vector provided a measure of how well the system models the input and output data for a set of parameters. The program was written using MATLAB software (Matlab R2018a, MathWorks®, Natick, Massachusetts, United States). Besides, ANFIS contained in the fuzzy toolbox of MATLAB software was employed to adjust the parameters of the fuzzy system used (18,19).

Controller Hardware: The designed controller consisted of four pads connected to an ATMega32 microcontroller (Atmel, San Jose, California, U.S.). Other peripherals used in the implementation system included four 220 ohm resistors and four pushbuttons. When the user pressed a pad (pushbutton inside the pad), the input signal to the microcontroller changed from the high voltage level to the low voltage level. After that, if the user released the button, the opposite happend; That is, the input signal to the microcontroller changed from the low voltage level to the high voltage level. The rising and falling edges created in the implemented fuzzy system were then used to decide and predict the command the user intended to send to the game. The system hardware was designed using Autodesk (Autodesk 9.2.0, Autodesk Inc., Coburg North, Victoria, Australia) and Altium Designer (Altium Designer 2018.1.7., Altium Limited, San Diego, California, United States) software. A schematic of the circuit designed for a pad with one of the final controller hardware pads (without top cover) is shown in figure 1.

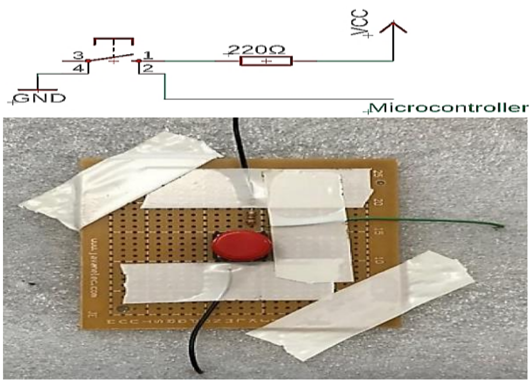

Figure 1. Circuit designed for a pad with its implementation without the top cover

Implemented fuzzy system: In order to improve the user experience of the designed controller, fuzzy logic was used as an adaptable and robust solution for processing the data received from the controller. In fact, a fuzzy system was responsible for classifying user commands. The controller could be used as a tool to simulate pressing and holding the button on the keyboard (similar to short and long pressing on touch screens). The task of converting the received input into a command was on the fuzzy system designed and adjusted. The above-mentioned fuzzy system parameters were determined by performing a series of tests in such a way as to provide a good experience for the user as much as possible, however since the proposed controller would be used by users with different ages and physical characteristics, the parameters were adjusted according to the user needs in the proposed system.

Fuzzy system inputs are fuzzy sets (18). Based on the time the user pressed the key, three membership functions were used to cover all possible scenarios. The controller output was basically the input of the fuzzy system and the output of this fuzzy system was the command that was sent to the game running on the main computer. The signal received from the user was divided into three categories by fuzzy sets as follows.

1. Very short signals: This condition occurred when the system was exposed to noise and the output changed unintentionally due to this noise. Naturally, the interval at which the controller output voltage level changed from high to low and then from low to high due to noise and unwanted signals was very short, and this feature could be applied to filter the effect of noise on the controller output signal.
2. Short signals: When the user pressed the controller pads to apply the Press command for a short time, the interval at which the output voltage level of the controller changed from high to low and then from low to high was longer than the previous state and shorter than the next state (Hold).
3. Long signals: Finally, when the user intended to send the Hold command, the output signal voltage level remained low for a longer period of time.

The most important challenge of this part of the fuzzy system design was to find the appropriate membership functions for the signal received from the controller. These membership functions determined the upper and lower limits of each state, as well as the transition between these states. Using the domain knowledge and performing some test samples, it was decided to use the sigmoid function for the very short and long states and a kind of Gaussian function for the short state. The sigmoid and Gaussian membership functions were defined as relations 4 and 5 (12).

$$\text{Sigmoid: } f(x; a, c) = \frac{1}{1+e^{-a(x-c)}} \qquad \text{Relation 4}$$

$$\text{Gaussian: } g(x; \sigma, c) = e^{\frac{-(x-c)^2}{2\sigma^2}} \qquad \text{Relation 5}$$

The Gaussian membership function used two sets of parameters; One set for the right curve and one for the left curve. The very short, short, and long membership functions before the system adjustment are depicted in figure 2 in terms of time.

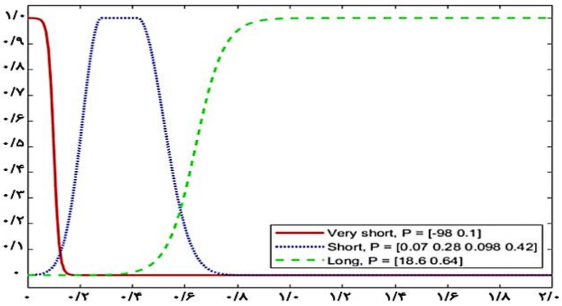

Figure 2. The very short, short, and long membership functions before the system adjustment

As mentioned arlier, in the proposed method, the zero-order Sugeno fuzzy model was used. The rules used in this system were defined as follows:

Rule 1: **IF** input is very short **THEN** output is ignore

Rule II: **IF** input is short **THEN** output is press

Rule 3: **IF** input is long **THEN** output is hold

The zero order Sugeno fuzzy model used returned -1, 0, and 1 for Ignore, Press, and Hold, respectively. The task of the system used was to obtain a nonlinear mapping between the membership functions and these values. Then the fuzzy system output was utilized to send the related command to the computer.

The initial values of the membership function parameters used were obtained by some pilot implementations. The most important factor in the fuzzy system design to be considered was the effect of the input membership functions on the user experience of the controller. By properly adjusting the parameters of the input membership functions, an effective communication of the user with the controller and the computer can be ensured.

The rate of change of the input membership functions has a huge impact on the user experience. For example, the membership function parameters for an adult have a much slower rate of change compared to the parameters set for a child due to differences in physical characteristics. Therefore, it can be concluded that the best way is to adjust the system parameters based on the current user of the controller. The proposed solution to this problem is to use an adaptive neuro-fuzzy system.

Results

As mentioned before, the membership function parameters play a very important role in the user experience. The most strategic way to set the fuzzy system parameters was to take data from the user and use them to change these parameters. The user was first asked to press the various controller pads. This data was stored in a dataset. Along with this data, a tag was used to specify the user command. In this method, the zero tag in the data set was considered as a Press operation. After this step, the user was asked to press and hold the different pads of the controller. For the Hold command, the label used was 1, which was stored in the dataset during the user communication with the controller. According to the rules mentioned in the previous section, the output of the fuzzy system along with an example of data collected from the user is demonstrated in figure 3.

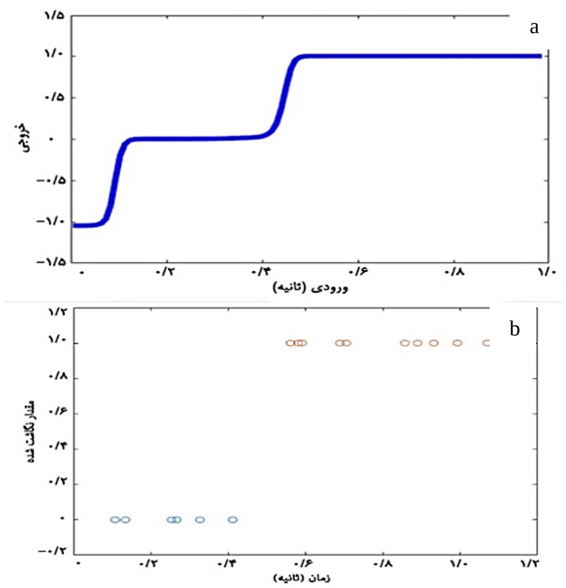

Figure 3. Fuzzy system output (a) with an example of the data collected from user (b)

During this process, an error tolerance rate had to be defined along with the number of iterations of this process. It was decided to set the error tolerance to 0.05 and to train the fuzzy system for 9 iterations. The backpropagation method was employed to update the parameters. After training the fuzzy system with the available data, the system error was around 0.03, which was acceptable given the limited number of data in the training data.

A very important step when setting up the system was to check whether the system was overfitting (21). In fact, one of the most important challenges when training a fuzzy system is to overfit the system with the available data. The limited number of data may cause the model to overfit. Given the limited data available, it makes sense that the number of iterations of the fuzzy system training steps is limited. Since the available dataset is unique to each user and collecting large amounts of data from the user causes their boredom and dissatisfaction, it can be argued that the initial values of the fuzzy system parameters are very important. These parameters must be quantified in such a way that, despite the limitations in the data received from the desired user, the algorithm used to adjust and modify the system parameters correctly converges (21).

When collecting data, some data points can be saved for use in the test phase. Furthermore, a number of training data can be used to extend the test data. Finally, it is important to note that to ensure the correct operation of the controller, it is important to separate some of the data collected from the user for the final testing of the system.

The system error diagram with the test result of the set fuzzy system is demonstrated in figure 4. The blue dots represent the data points and the red stars indicate the output of the fuzzy system. It can be clearly observed that all data points in the test data, except for data number 4, were correctly estimated by the fuzzy system, which is why the blue dots are not easily seen in figure 4.

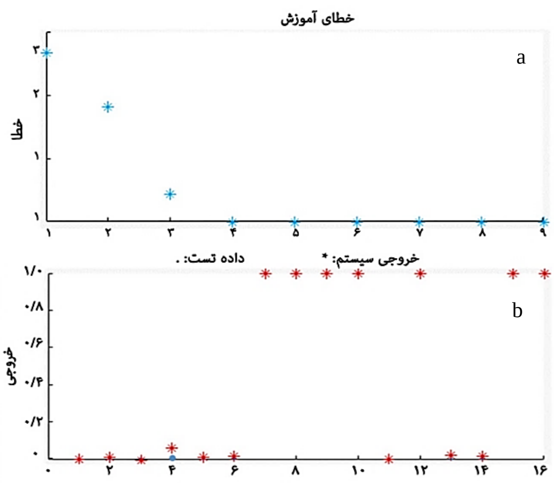

Figure 4. System error during training (a) along with test result of the fuzzy system set (b)

Given that the system error was around 0.03, it is not unreasonable to round the fuzzy system output to ensure the correctness of the system output. During the test phase, after rounding the fuzzy system output, all the outputs of the system were obtained correctly. Given the acceptable performance of the fuzzy system, it can be claimed that the system has not been over-fitted and the training phase has been successful.

Integration of fuzzy system and controller hardware: In this section, the trained fuzzy system was used to manage the data received from the controller. As mentioned earlier, the raw data obtained directly from the controller did not provide a pleasurable experience for the user, and hence, changes were made to the data received from the controller using the fuzzy system. The fuzzy system then sent the appropriate command to the game running on the main computer by analyzing the user-controller communication. The program was implemented in such a way that the main computer read the data from a microcontroller to which it was connected. Any change in the amount of the data received was analyzed by the fuzzy system and a command related to the game being played was sent. These commands included pushing buttons, holding buttons, and standby mode. When the user pressed a button, the voltage level of the signal received from the controller changed from high to low.

The membership functions used in the system determined the similarity of the command received from the user to one of the Press or Hold commands. The command received from the user was determined by the rising or falling edges and by setting a counter. As soon as the falling edge was received from the controller, the counter started counting to save the time the user had pressed the pad. As long as the user had held his hand on the pad, the value of this counter was sent to the fuzzy system. It should be noted that this counter was actually the fuzzy system input and all the decisions made by the controller were in fact the fuzzy system output. Reaching the lower limit of the Hold operation, when the firepower of the input membership function led to the Hold operation, the fuzzy system sent the command of this operation to the game. It is clear that the sent command changed based on the changes in the position of the compressed pad.

Another state occurred when the user intended to press the key. In this case, first a falling edge was detected and after a short time, a rising edge was detected. This situation occurs when the user presses and releases the key to send the Press command. When the rising edge was detected in the controller output signal, the counter value was sent to the fuzzy system and then the counter was set to zero again. The fuzzy system then determined whether the user's desired command was Press. When no button was pressed or held, the amount received from the controller might change due to noise, but since the implemented system was robust using the fuzzy system (12), it could be guaranteed that the effect of noise on the controller output did not affect the overall performance of the system. The pseudo-code of the implemented system is as follows:

```
while controller is operating:
    read data from controller
    check read values from differnet pins:
        if a falling edge was detected:
            increase counter
            send the value of counter to fuzzy logic system
            check the output of the fuzzy logic system
            if output=1:
                send the corresponding hold command
        if a rising edge was detected:
            send the value of counter to fuzzy logic system
            check the output of the fuzzy logic system
            if output=0:
                send the corresponding press command
            reset counter
        if output=-1:
            do nothing
```

The designed system can be used for different video games that are controlled by four different commands. Platformer Games are a great example of games that can easily be controlled by the proposed controller. Similarly, Maze Arcade games like Ms. Pac-Man (Midway Games, USA) can also be played with this controller. The only remaining step before using the controller is to configure the controller and define a list of keys required for different commands for the controller. The controller was designed in such a way that it sends various commands to the user to control the game using a list prepared by the user. For example, for the Ms. Pac-Man game, only four direction keys are needed to play. After configuring the controller, the game command is sent when the user presses or holds a pad. This controller supports all keyboard keys and using the graphical user interface provided, the user can easily configure and adjust the controller. The user can easily determine which command each pad sends to the game. The list of special keys includes keys such as Space, Enter, and arrow keys, which are widely used in various game styles. Furthermore, the user is able to view the status of the controller using the label at the end of the user interface. For example, when the controller is ready to send user commands to the game, the user will see a Ready message in the graphical interface. In addition, the controller can be adjusted using the Calibrate key. Pressing this key starts the controller setting process described earlier. The controller connects to the main computer via a USB port, and the port will be occupied as long as the controller software is running. Therefore, it is very important to consider two keys called Run and Disconnect in order to manage the computer's USB port. The controller graphical interface with full function and the Ms. Pac-Man game running on the main computer can be seen in figure 5.

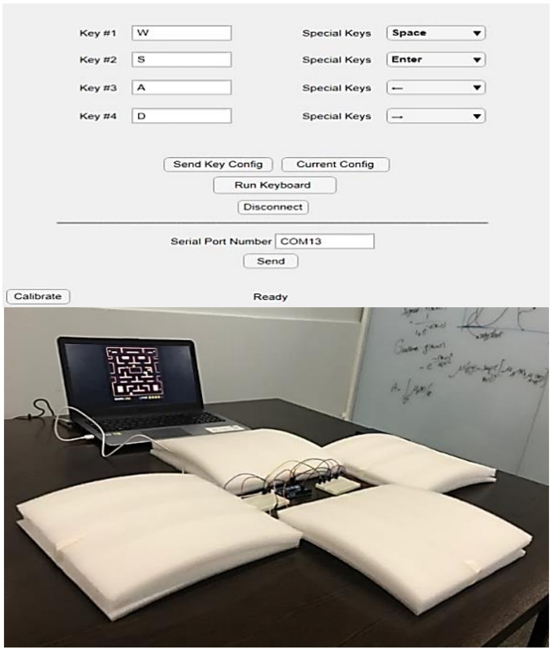

Figure 5. Controller graphical interface with full function and the Ms. Pac-Man game running on the main computer

Discussion

In the present study, an adaptive neuro-fuzzy system embedded in a controller effective for exergames was designed and implemented. The adopted method required no additional accessories such as cameras or sensors, hence reducing the costs of implementing the system, which is one of the advantages of this design. This controller can be applied in harsh environments as it depends only on the signals received from the pads and factors such as light and ambient temperature do not affect its performance. Besides, the neuro-fuzzy system used is able to provide the best experience for the user according to the user behavior as well as the requirements of the game.

When the user is using the keyboard, it is very easy to distinguish between pressing and holding the key equivalent to short and long pressing in touch screens. In exergame controllers used by users with different physical characteristics, the process of classifying user commands can be very complicated. It can be argued that the different controller users need different mapping of the signals received from the pads to the commands sent to the game running on the main computer. This mapping is performed using different membership functions. In fact, by changing the parameters related to the membership functions, it is possible to adjust the controller according to the user physical characteristics. Additionally, using the adaptive neuro-fuzzy system, the initial values of the parameters of the membership functions can be determined using the existing domain knowledge. This domain knowledge greatly facilitates the adjustment of parameters of the membership functions. An important issue when designing the proposed system that should be given much attention is the impossibility of collecting large data in order to adjust the system. For this reason, having the right initial values for the system parameters was essential. Therefore, it can be argued that the use of an adaptive fuzzy system as a controller in games is inevitable.

Classifying player behavior based on hard calculations leads to user dissatisfaction; because he will not be able to communicate effectively with the system. Therefore, even if the game running on the system has a good quality of entertainment, due to the lack of soft calculations, the user will not be satisfied with the result. In the proposed method, the problem is solved by collecting the signal from the user. In fact, the membership function parameters used in the proposed fuzzy system are adjusted by the data received from the user so that the controller has an acceptable performance. On the other hand, designing specific games for a controller is not practical (22); this is because it restricts the user’s options and also, the controller can only be used for certain games. However, by analyzing the signals received from the controller, it can be easily adjusted for different games. By setting the controller, it is possible for the controller to respond to the user’s commands effectively and accurately. In the proposed system, the user is asked to press or hold the pads several times to train the system based on his physical characteristics. For example, the time it takes for a child to press a pad is much shorter than for an adult (23). The collected data is then used to change the parameters of the fuzzy system designed so that the controller provides a pleasurable game experience for the user using the domain knowledge. One of the most important applications of this system is motor and mental rehabilitation of individuals with trauma or chronic diseases. These patients need long-term rehabilitation due to the loss of motor skills, and adapting the game to their level of ability, the possibility of developing the game in proportion to the individual’s progress, and preventing boredom during the game due to the long rehabilitation process are important principles in their treatment. The designed controller was able to meet these three basic needs in this area of serious gaming.

Limitations

The implemented system used an ATMega32 microcontroller, and naturally the limitations of the implemented hardware are closely related to the limitations of this microcontroller. For example, the implemented system can manage a limited number of pads as the system input.

Recommendations

Given that the ability to transfer technology from one implementation to another with the help of fuzzy logic is possible, the authors seek to design and implement a circuit to standardize the signal received from different sensors according to the rules used in the fuzzy system to allow the designed software be used for other sensors.

Conclusion

The proposed controller is connected to the main computer, which receives commands from the user to communicate with the game running on the main computer through the embedded pads. The user of this controller can simulate holding and pressing the key through these pads. The proposed controller can be used for exergames to improve the user physical condition and health.

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Authors' Contribution

Kiavash Fathi: Study ideation, implementation and troubleshooting, monitoring the implementation process, providing required equipment and components, collecting and analyzing system data, training the implemented system, system software and hardware integration, manuscript preparation, specialized and grammatical evaluation of the manuscript in terms of scientific concepts, approval of the final manuscript to be submitted to the journal office, the responsibility of maintaining the integrity of the study process from the beginning to the publication, and responding to the referees' comments; Afrooz Laghaei: Study ideation, implementation and troubleshooting, monitoring the implementation process, providing required equipment and components, collecting and analyzing system data, training the implemented system, system software and hardware integration, manuscript preparation, specialized and grammatical evaluation of the manuscript in terms of scientific concepts, approval of the final manuscript to be submitted to the journal office, the responsibility of maintaining the integrity of the study process from the beginning to the publication, and responding to the referees' comments; Javad Rasti: Study ideation, monitoring the implementation process, providing required equipment and components, system software and hardware integration, manuscript preparation, specialized and grammatical evaluation of the manuscript in terms of scientific concepts, approval of the final manuscript to be submitted to the journal office, the responsibility of maintaining the integrity of the study process from the beginning to the publication, and responding to the referees' comments; Maryam Zekri: collecting and analyzing system data, training the implemented system, manuscript preparation, specialized and grammatical evaluation of the manuscript in terms of scientific concepts, approval of the final manuscript to be submitted to the journal office, the responsibility of maintaining the integrity of the study process from the beginning to the publication, and responding to the referees' comments.

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Conflict of Interest

The authors declare no conflict of interest. The idea behind the study in the current phase has only a research aspect.

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