Simulation and Visualization of Intelligent MIMO-ANFIS-Based Control System in Virtual Reality using MATLAB and V-Rep

Mokhles M. Abdulghani
Jackson State University
Jackson, Mississippi
mokhles.m.abdulghani@students.jsums.edu

Wilbur L. Walters
Jackson State University
Jackson, Mississippi
wilbur.l.walters@jsums.edu

Khalid H. Abed
Jackson State University
Jackson, Mississippi
khalid.h.abed@jsums.edu

***Abstract*—The noteworthy increase in processing power of computers with the excess of open software and hardware standards has significantly changed the landscape in the field of 3D virtual robotics simulation platforms. Employing software computing tools, such as fuzzy logic, neural networks, and genetic algorithms, encouraged researchers to design intelligent systems that mimic human behavior. Designing a Multiple-Input Multiple-Output (MIMO) control system using Adaptive Nuero-Fuzzy System (ANFIS) offers easy and reliable solutions to generate the desired outputs without the need for a complex mathematical model. This paper shows a MATLAB-based MIMO ANFIS control system for two different robotic systems: a two-wheel drive (2WD) mobile robot and a six-degree of freedom (6DOF) robotic arm. The Virtual Robot Experimentation Platform (V-Rep) has been used to test the designed systems through a direct interface with the MATLAB Simulink. The results showed an acceptable error value of 0.002% in generating the desired outputs of the 2WD robot. On the other hand, the performance of the implemented ANFIS controller for the 6DOF robotic arm showed a high error value of 30% if the proposed method is used to design MIMO-ANFIS control system.**

***Index Terms*—** *MIMO ANFIS, V-Rep, Obstacle avoidance Control, MATLAB, Simulink, 3D simulation, Real-time Control, ANFIS.*

I. INTRODUCTION

Soft computing is a set of algorithms, including evolutionary algorithms, genetic algorithms, fuzzy logic, and neural networks. These algorithms are designed to efficiently adapt with uncertainty, imprecision, partial truth, and approximation [1], [2]. Fuzzy logic implements computing based on degrees-of-truth rather than the usual true-or-false Boolean logic. The idea of fuzzy logic was first introduced by Lotfi Zadeh of the University of California at Berkeley in the 1960s. Artificial neural networks are used in simulations of various problems and can perform just as well as fuzzy logic in many cases, while genetic algorithms could perform as optimization tools.

The main advantage of using fuzzy logic is dealing with indefinite or vague information in the provided set of inputs and approximate reasoning. While neural networks have the positive features of learning and adaptation, which are missing in fuzzy logic. Merging the concept of neural network and fuzzy logic offers a great combination of capability for providing an opportunity to overcome their limitations and maximize their strengths [3], [4].

The Adaptive Fuzzy Nervous System (ANFIS) is an effective hybrid technique comprised of a Fuzzy Inference System (FIS) supported by neural network-based optimization. ANFIS can be designed using MATLAB fuzzy logic toolbox [5] that offers both Mamdani and Sugeno fuzzy inference system. Until the time of writing this article, this toolbox offers only designing a Multiple-Input Single-Output (MISO) ANFIS controller; therefore, more efforts are needed to implement a Multiple-Input Multiple-Output (MIMO) ANFIS controller. Furthermore, designing MIMO ANFIS algorithms is a big challenge, especially in real-time applications [6].

In the ANFIS, the membership functions and rules are produced automatically by the adaptive neural network and could be used to generate the best fit to the desired output from training data [7].

III. RELATED WORK

In [8], the author proposed an ANFIS controller with two outputs was designed for control of two-wheel drive (2WD) mobile robot. The proposed controller converts the left and right motor speed to one steering angle that was calculated using the mathematical model of 2WD mobile robot. The system was trained using a set of 15 rules in MATLAB fuzzy logic toolbox. The designed algorithm was converted to C++ code using the MATLAB code generator and uploaded to ARDUINO microcontroller. In the suggested method an accurate mathematical model for the controlled system was required to calculate the required outputs (steering angle). Furthermore, for a system with many distance measurement sensors, a complicated calculation will need a high computing power to produce the required outputs as a result.

In [9], MIMO ANFIS-based control system was suggested for collision avoidance control of a 2WD mobile robot. An ANFIS controller has been designed separately for each of the left and right motors. The desired speed output of each motor was trained using MATLAB ANFIS toolbox. The suggested control system was comprised of two ANFIS algorithms and each one needed to be operated by a separate microprocessor or microcontroller.

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In [10], the authors proposed another control approach with two Mamdani-type fuzzy inference systems to control a two-wheel differential drive mobile robot. Training data was collected from left and right motors for use in neural network training. The proposed algorithm was implemented in MATLAB and gives good accuracy. It is difficult to deal in the same way with a complex system that has many inputs and outputs due to the need for massive training data.

Coactive Neuro- Fuzzy Inference System (CANFIS) is an extension of ANFIS based on MIMO system [11]. The input range of CANFIS is divided into three different parts to group the data using neural network technique. Further calculations are required with special software to implement the CANFIS technique. It is difficult to employ this approach when dealing with MIMO systems where they need to cover and train many control cases.

Virtual Robotic Experimentation Platform (V-Rep) is an open-source 3D simulation framework used for system design, testing and verification. Currently V-Rep is widely used as robotic simulator and controller. It performs several tasks during planning and implementation phases. These tasks include system verification, algorithm optimization and realization, simulation of complex systems, robot task planner and controller [12]. For testing the ability of the proposed ANFIS algorithms and general system behavior, 3D V-Rep was used in this research. In fact, the 3D visualization simulation is the best way to see the resulting system behavior in the virtual world. One of the most used ways to simulate MATLAB work in 3D visualization is by interfacing the MATLAB with V-Rep framework. The most used approach to interface the MATLAB/SIMULINK environment with V-Rep is by using robot operating system communication libraries for prototyping of robot control algorithms [13], [14].

This paper is a follow-up work for our previous work [15]. The design and evaluation of simple MATLAB-based MIMO ANFIS controllers will be implemented in V-Rep. The rest of the paper is ordered as follows. The design methodology of the proposed MIMO ANFIS controllers is given in section III. The direct interface between MATLAB-Simulink and V-Rep, and the application of the proposed MIMO ANFIS controllers for a 2WD mobile robot and for a 6DOF KUKA robotic arm are presented in section V. Simulation results are discussed in Section IV. Finally, the conclusion is given in Section VI.

III. Methodology of The MIMO-ANFIS

Since the ANFIS toolbox in MATLAB offers a design tool for a MISO-ANFIS controller, an additional ANFIS design is required for each individual output to implement a MIMO-ANFIS.

A. Data Preparation:

The values of selected output were prepared as a dataset according to the given input values in each system. Involving as many cases as possible will strengthen the accuracy of the system in the data training stage. The same dataset will be trained separately for each output using the ANFIS toolbox in MATLAB. The designed ANFIS controllers are MISO, and the number of the designed controllers is equal to the number of outputs in each system.

B. MISO ANFIS Design:

All the required cases (inputs & outputs) in the dataset were trained using the ANFIS toolbox in MATLAB with a Mamdani FIS. For the training process, the values of the training parameters of the proposed ANFIS algorithm are given in Table I.

Table I. ANFIS Training Parameters

Influence	0.43
Squash	1
Accepting rate	0.25
Rejecting rate	0.15

C. MIMO ANFIS Design:

The designed MISO ANFIS controller for each output using the same training data with the same training parameters has been converted to C++ code using the code generation option offered in MATLAB. Then, we merged the output values for the same inputs in each of the MISO C++ codes in one new C++ code by adding the resulting outputs values (rules) and build C++ MIMO ANFIS. The generated C++ code can be easily uploaded to a microcontroller to test it in real time or can be tested in virtual reality as we did in this paper.

D. Preparing V-Rep Modules:

An efficient method was developed to interface the MATLAB-Simulink with the open-source 3D simulation engine V-Rep platform. MATLAB lacks an efficient 3D simulation option to visualize the results, specifically the robotics systems. Hence, V-Rep platform is a good choice as an alternative simulator, where it is an open source and freely available to research applications. In this case, 3D simulation becomes widely spread in robotics system. With V-Rep it is possible to simulate different robotic models like KUKA, PUMA, and PIONEER robots. The V-Rep offers many different possibilities to include its own code or to interface with external software. A direct interface between SIMULINK and V-Rep software has been successfully achieved through four steps. Firstly, preparing a V-Rep model to test the designed ANFIS controller. The second step is preparing a SIMULIMK model for the ANFIS controller. While, during the 3rd & 4th steps, a MATLAB script code has been designed to send and receive data between SIMULINK & V-Rep. The Pioneer and KUKA robot models have been used to simulate the proposed MIMO ANFIS controllers and implement the obstacle avoidance and cups filling tasks. The Pioneer model is equipped with 16 ultrasonic sensors, 6 of them have been used to test the resulting MIMO ANFIS controller for the collision avoidance task. While the KUKA model is equipped with 6 servo motors, all of them have been used to test the resulting MIMO ANFIS controller for the cups filling task.

E. Simulation of the MIMO ANFIS Controllers:

Fig. 1 shows the implemented interface between SIMULINK and V-Rep. Fig. 2 presents the implemented ANFIS controller of the 2WD mobile robot using Simulink performing collision avoidance tasks. Each of the MISO ANFIS controllers (for the left and right motors) will receive feedback signals from six ultrasonic sensors provided with the 2WD Pioneer robot and produce the output according to the training data. The sensors reading received in meters from the V-Rep are converted to centimeter in the Simulink model using Gain and MATLAB function blocks for each input. The ANFIS controller produces the output as a PWM signal then it will be converted to a rotation speed in round per minute (RPM) to be sent to the V-Rep Pioneer model.

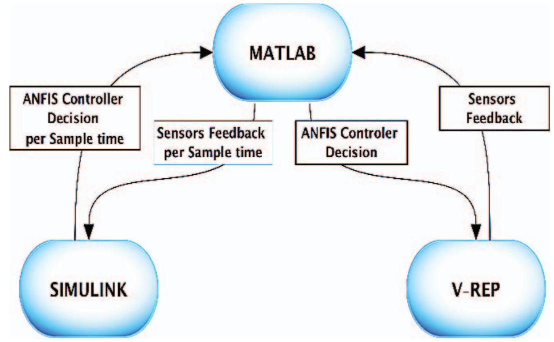

Fig. 1. Data Flow During the Direct Interface between V-Rep MATLAB-SIMULINK.

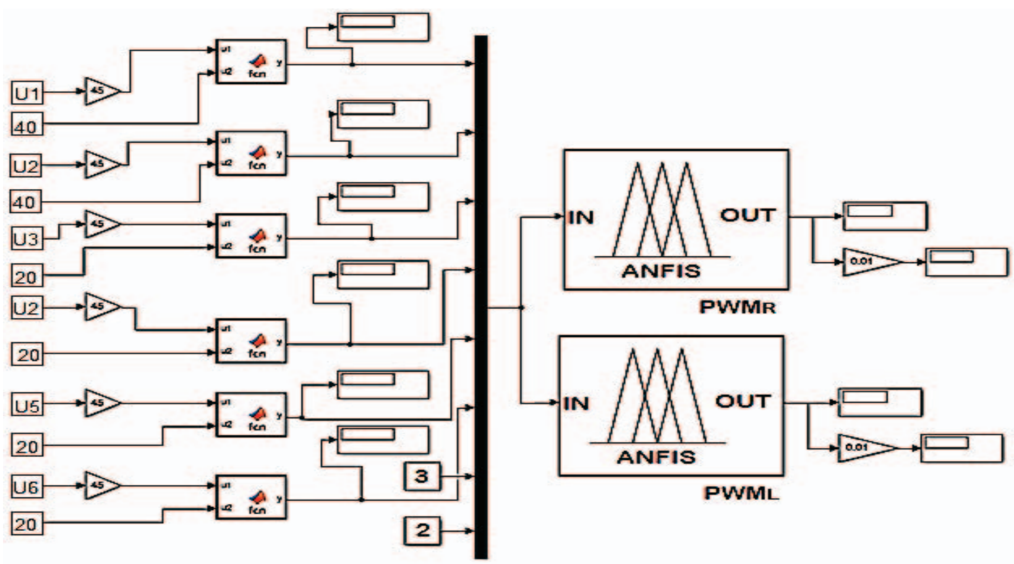

Fig. 2. MIMO ANFIS Simulink model for a 2WD mobile robot.

F. Direct Interface Between V-Rep and MATLAB:

MATLAB starts the communication with the V-Rep and reads data from the robot sensors through a set of commands written in script code. The remote API function in the V-REP software has been used to define the required variables to be received and sent from V-Rep to Simulink. In case of connecting the MATLAB script code to the V-Rep, the asynchronous mode should be selected which means that MATLAB and V-Rep will run in parallel by sending data and commands back and forth.

To start reading data from the V-Rep using the asynchronous mode all the variables need to be defined in the MATLAB script code for each of the 6 ultrasonic sensors and for the two motors in the Pioneer mobile model. The 2 sensors measuring the height on the back and the front of the wheelchair have been set as constant input values. The command ("set_parm") has been used in the MATLAB script code to update the Ultrasonic sensors readings in the Pioneer robot in V-Rep with sampling rate of 0.01 seconds. The following function has been used to define the V-Rep variables needed to communicate with the Simulink model:

```
[number returnCode] = s
imxAppendStringSignal(number clientID, string
signalName,string signalValueToAppend,number
operationMode)
```

In the same constructed script code in MATLAB, a communication with the V-Rep has been designed to write the output commands produced in the Simulink model of the

ANFIS controller to the two motors of the Pioneer robot during its movement. To keep V-Rep and Simulink running with asynchronous mode, the Pioneer robot model should continuously receive the updated command in each sample of the Simulink model.

The command ("get_parm") has been used in the MATLAB script code to update the motors speed of the Pioneer robot in V-Rep according to the produced PWM signal from the simulated ANFIS controller. Then, the received variables from Simulink will be sent using the following remote API function to the Pioneer robot model in V-Rep software:

```
[returnCode]=vrep.simxSetJointTargetVelocity(clientID,left_Motor,l,vrep.simx_o1pmode_blocking)
[returnCode2]=vrep.simxSetJointTargetVelocity(clientID,right_Motor,r,vrep.simo2_opmode_blocking)
```

where (l and r) variables are the control output commands for the 2WD mobile robot represents the rotational speed of the left and right motor respectively. The same sampling rate has been chosen (0.01 second) for each output to keep the system working in asynchronously.

IV. Performance Visualization

Fig. 4 shows the 2WD Pioneer mobile robot that was used to test the collision avoidance task. The Pioneer model is equipped with 16 Ultrasonic sensors, 6 of them have been used to test the resulting ANFIS controller for the collision avoidance task. 55 cases have been used to train the ANFIS controller of 2WD mobile robot. Table II shows a sample of these cases. The inputs (U1-U6) represent the readings from 6 Ultrasonic sensors distributed on the body of the mobile robot.

Fig. 4. Pioneer 2WD mobile robot model.

Table II. Sample of The Training Data of The 2WD Mobile Robot

U1	U2	U3	U4	U5	U6	LMPWM	RMPWM
40	40	20	20	20	20	100	100
35	40	20	20	20	20	75	100
40	35	20	20	20	20	100	75
30	40	20	20	20	20	60	100
40	30	20	20	20	20	100	60
25	40	20	20	20	20	50	100
40	25	20	20	20	20	100	50
20	40	20	20	20	20	40	100
40	20	20	20	20	20	100	40
15	40	20	20	20	20	30	100

The outputs (RMPWM and LMPWM) are the required PWM signals to be generated for the right and the left motors. The dataset has been used to design two controllers using ANFIS tool in MATLAB, one for each output in the 2WDmobile robot. The resulting controllers have been merged into one controller to construct a MIMO ANFIS by adding the output data from one of them to the other.

Another application is to check the ability of the proposed MIMO ANFIS, where a KUKA robotic arm with 6DOF is used to perform the task of filling set of cups on the table, as shown in Fig. 5. The KUKA model is equipped with 6 servo motors, all of which are used to test the resulting ANFIS controller for cup filling function. Only 20 cases were used to train the ANFIS controller from the robotics arm. Table III illustrates some of these cases. The Inputs X, Y, and Z represent the position on the table in meters, as given in Fig.6. The reference cup of position (0,0,1) is the first lower one on the left. The outputs (Y_1-Y_6) represent the degrees of movement that must be performed for each of the six joints of the 6DOF robotic arm to reach the desired position. As we did in the 2WD MIMO ANFIS controller, the same was performed for the 6DOF robotics arm by converting the resulting MISO ANFIS for each output to C++ code and then merging them all in one C++ code.

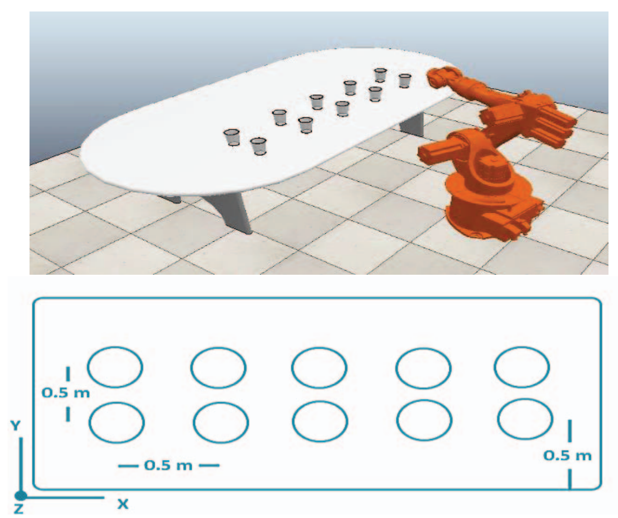

Fig. 5. KUKA 6DOF robotic arm model.

TABLE III. SAMPLE OF THE TRAINING DATA OF THE 6DOF KUKA ROBOT CONTROLLER

X (m)	Y (m)	Z (m)	Y1	Y2	Y3	Y4	Y5	Y6
0	0	1	-48°	-23°	-13°	0°	-11°	0°
0.25	0	1	-33°	-22°	-13°	0°	-11°	0°
0.5	0	1	-24°	-21°	-13°	0°	-11°	0°
0.75	0	1	-16°	-13°	-16°	0°	-12°	0°
1	0	1	-09°	-04°	-16°	0°	-15°	0°
1.25	0	1	-1°	-13°	-13°	0°	-12°	0°
1.5	0	1	10°	-21°	-13°	0°	-12°	0°
1.75	0	1	23°	-22°	-13°	0°	-11°	0°
2	0	1	38°	-21°	-13°	0°	-11°	0°
0	0.25	1	46°	-22°	-13°	0°	-11°	0°

V. RESULTS AND ANALYSIS

The control interface between MATLAB Simulink and V-Rep simulator is an interesting approach to simulate any mechatronic system. With simple programming skills on the MATLAB scripting and using the remote API commands of the V-Rep, it was easy to test the resulting system on a 3D model. Fig. 8 demonstrates the performance of the Pioneer robot model in the V-Rep, where the MIMO ANFIS can navigate the mobile robot to avoid collisions in the working area. This controller showed the ability to generate the required outputs even with uncertain cases.

The performance of KUKA robotic arm was insufficient using the implemented MIMO ANFIS controller because of the high error value (about 0.3) in the output values. Fig. 9 presents the implementation of the cups filling task with the designed MIMO ANFIS controller where (•) is the actual position and (+) is the desired position. In this MIMO system, it is difficult to design MIMO ANFIS controller with input membership functions that can satisfy all the possible cases for six outputs (6 servo motors). Additionally, the six motors of the robotic arm are asymmetric which makes the number of the required membership functions in the output range extremely high.

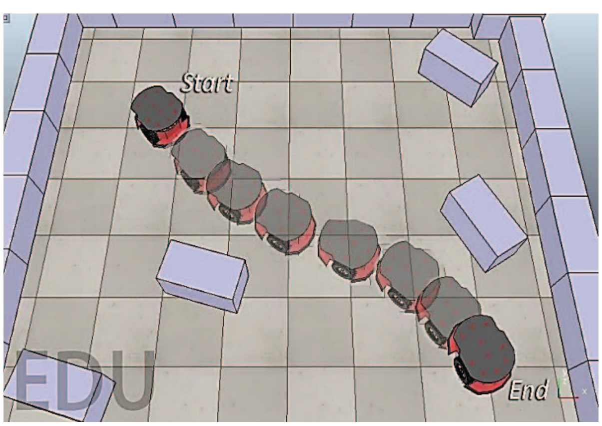

Fig. 8. V-Rep Simulation for the 2WD robot during the collision avoidance task.

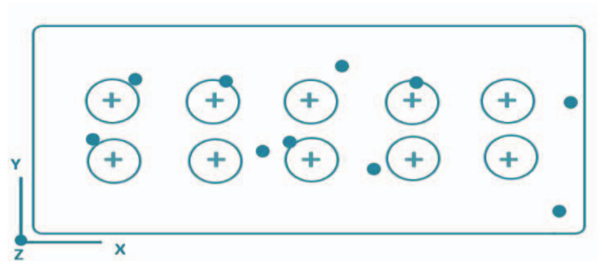

Fig. 9. Implementing the cups filling tasks by the 6DOF robotic arm using designed MIMO ANFIS controller.

VI. CONCLUSIONS

MIMO ANFIS was successfully implemented and simulated with MATLAB and V-Rep. The direct interface between MATLAB Simulink, and V-Rep 3D simulation platform is a remarkable method to simulate any robotic system. With simple programming skills using MATLAB, Simulink and using the remote API of the V-Rep it was possible to test the resulting system on a 3D model. The resulting control system is MIMO ANFIS that works with error value ($2*10^{-5}$) to produce the required PWM signal for each motor in the 2WD mobile robot. The resulting system demonstrates the ability of the MIMO ANFIS controller for a mobile robot to take action to avoid collisions during testing in a 3D virtual environment. However, in the 6DOF robotic arm MIMO ANFIS control system did not perform well due to the ANFIS architecture and training issue with the six outputs in addition to the different actuating elements on each joint. More dataset and training might be required to overcome this problem.

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