Haptic Paddle and Fuzzy Based Virtual Environment Model Control System as a Didactic Tool

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***Abstract* – The paper deals with design, construction and implementation of bilateral control system using fuzzy regulation. The aim of paper is implementation of a system which can be used as a didactic tool for better understanding of bilateral control concepts, as well as a base for further work. The system is composed of mechanical model of haptic paddle with one degree of freedom and virtual model of haptic paddle and its environment, interconnected using acquisition card. Virtual environments control is created using fuzzy logic. After implementing control algorithm and connecting two models – the mechanical and virtual, the functionality of system was confirmed by experimental data.**

***Keywords:* haptic, virtual reality, fuzzy, position dependent control, speed dependent control, friction force**

I. Introduction

Haptic relates to sense of touch, in particular, to the perception and manipulation of objects using the senses of touch and proprioception [1]. The word derives from the Greek *haptein*, meaning “to fasten”. By using manually controlled input/output devices (joysticks, data gloves or other devices), users can receive feedback from computer applications in the form of felt sensations via the hand or other parts of body. In combination with a visual display, haptic technology can be used to train people for tasks requiring hand-eye coordination, such as surgery and space ship maneuvers. It can also be used for games in which the interactions with images are seen, but also felt [2] [3].

Over the last decade, researchers in the haptic community have been developing low-cost haptic devices to make the science, technology, engineering and math theory closer to students by physical implementation. [2-6]

This paper describes a similar solution. The goal was to construct and implement a system which can be used as a platform for practical development and testing of different control algorithms and methods. This approach offers a better understanding of theoretical concepts of bilateral control in educational process.

In order for the mechanical model to be compatible with available NI acquisition card, as well as the easy-to-operate feature, following requirements are to be met:

- mechanical model outputs are DC voltage signals representing current, speed and position of haptic paddle
- mechanical model input is DC voltage signal for motor control, providing the user with feedback from the virtual model thus allowing bilateral control to be implemented
- calibration of haptic paddle position.

The virtual model is developed as a pair device for the mechanical model. This allows low cost bilateral control to be implemented without having to construct two mechanical models. Virtual models, represented in this paper, were created using 3DS MAX software package and incorporated in Matlab/Simulink model. This way the system flexibility is achieved because of already existing toolboxes inside Matlab/Simulink which provide students with amount of different control options that can be used and implemented.

In this paper, five virtual environments are modeled using fuzzy logic. The block scheme of the system is shown in Fig. 1.

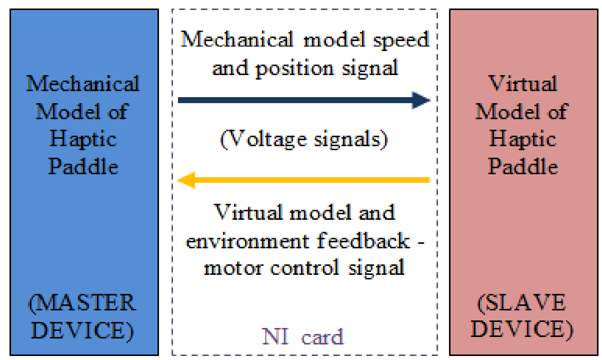

Figure 1. Block scheme of implemented system

The paper is organized as follows. Mathematical model of haptic paddle is described in Section II. Section III describes electromechanical model of haptic paddle, while Section IV deals with virtual modeling of haptic paddle and different environments. Implementation of fuzzy control in virtual models is described in Section V. Experimental results are shown in Section VI and conclusion is given in the last section.

II. Mathematical Model of Haptic Paddle

Mathematical model was not used for control algorithm implementation in this paper because of fuzzy based control. Nevertheless, it can be significant for future work.

As a laboratory tool, the haptic paddle is an example of a typical second-order mechanical system upon which students can experiment. The dynamic model of the haptic paddle is similar to that of the classic inverted pendulum. By measuring the frequency of oscillation of the paddle sector pulley and center of mass, an estimate of its inertia can be found [7].

By observing the created haptic paddle system, it can be divided in two subsystems: the mechanical system, which is represented by the paddle, and the electromagnetic system, which is represented by the motor and the amplifier.

Equations of motion of the haptic paddle, which can be used for describing this system, are given in [7] as:

$$\begin{gathered} J_{eq}\ddot{\theta} + \ b_{eq}\dot{\theta} + k_{eq}\theta = T \\ J_{eq} = J_s + m_s r_{cg}^2 + J_m N^2 \\ b_{eq} = N^2 b_m \\ k_{eq} = -m_s g r_{cg} \\ T = N(\tau - \tau_f) \end{gathered} \qquad (1)$$

Where θ is the angle of the paddle, b_{eq} is equivalent friction, J_{eq} is equivalent inertia, k_e is equivalent stiffness coefficient, J_s is moment of inertia of the sector pulley, m_s is mass of the sector pulley, r_{cg} is distance from center of mass to center of rotation, J_m is inertia of the motor, N is paddle gear ratio, b_m is viscous friction in the motor, g is acceleration due to gravity, τ is torque applied by the motor and τ_f is Columb friction in the motor.

The equation describing the behavior of the DC motor, by assuming that Coulomb friction and the viscose friction in the motor are negligible, is:

$$\begin{gathered} J_m\dot{\omega} + b_m\omega = 0 \\ \omega(t) = \omega_0 e^{-\frac{b_m}{J_m}t} \end{gathered} \qquad (2)$$

The haptic paddle is an unstable system in the absence of feedback control, because the equivalent stiffness due to gravity is negative [7]. Adding proportional feedback in the system compensates for its instability. The effect of the feedback control is described by the following equation:

$$\begin{gathered} T = K_p\theta + K_v\dot{\theta} \\ J_e\ddot{\theta} + \ (b_e - K_v)\dot{\theta} + (k_e - K_p)\theta = 0 \end{gathered} \qquad (3)$$

III. Electromechanical Model of Haptic Paddle

The electromechanical model of haptic paddle was built according to the requirements described in Section I. As shown in Figure 1, the model has one input – motor control signal and two outputs – speed and position of haptic paddle. Considering the flexibility and possible future work on this model, one output signal – motor current, although not used, was added. All input and output signals are voltage signals, including the motor current signal which is, although dimensionally in Amperes, available as a corresponding voltage signal in Volts, in range from 0V to 1V, therefore corresponding to motor current range from 0A to 1A. The block scheme of electromechanical model is shown in Fig. 2.

One of system requests was calibration of haptic paddle which is implemented using microcontroller (development system SUBOARD II with PIC 18F4550 microcontroller). There are two operation modes of electromechanical model of haptic paddle – reset and running mode.

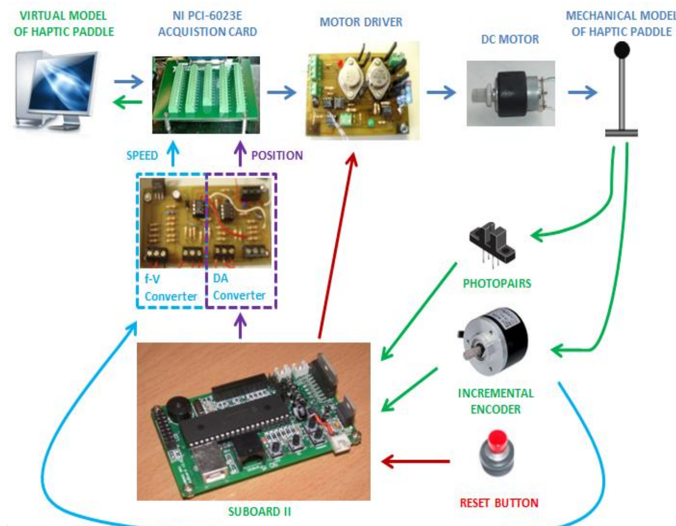

Figure 2. Block scheme of electromechanical model

Reset mode is triggered by reset button. DC motor control signals are generated by microcontroller which is using information from photopairs for calibration algorithm. This brings the paddle in starting, central position (orthogonal to base of mechanical model). Paddle has angle movement range from -60° to +60° in regard to starting position of paddle. All three characteristic positions of the haptic paddle – central position and limits at -60° and +60° are, when reached, detected by photopairs. This is used when paddle is being calibrated and it also prevents the haptic paddle from going out of its operating range. The flowchart representation of calibration algorithm is shown in Fig. 3.

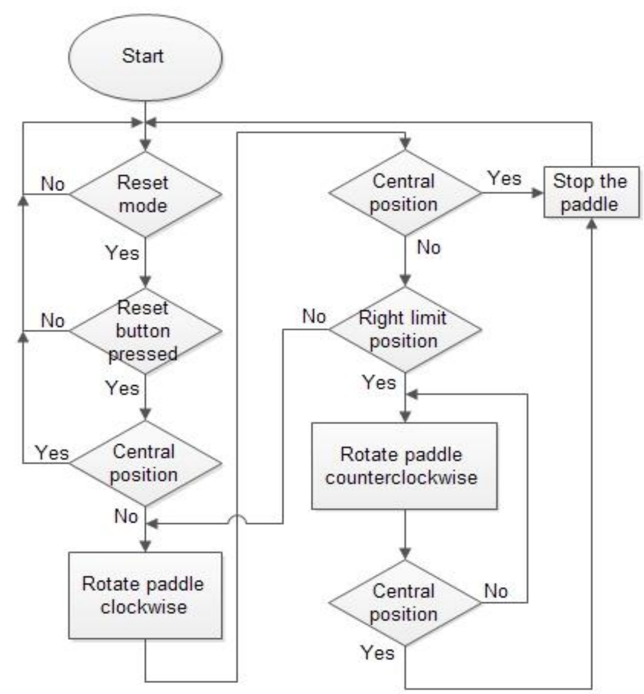

Figure 3. Flowchart of reset button triggered paddle calibration

In running mode, DC motor input signal is generated as a feedback from virtual model and environment by using NI acquisition card. Range of motor control voltage signal, for both modes, is from -10V to 10V. The change of operation mode is easily done using switch on motor driver board.

The implemented mechanical model is shown on Fig. 4.

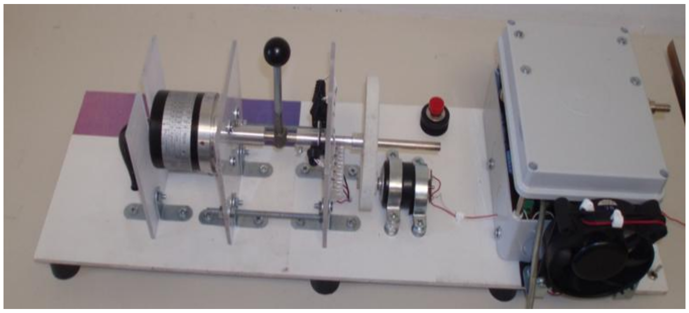

Figure 4. Mechanical model of haptic paddle

BALLUFF BDG 6360-1-05-2500-65 incremental encoder is used to measure speed and position of haptic paddle. Encoder signal is converted to a voltage unipolar signal using frequency to voltage converter KA331. Voltage output of KA331 is in range from 0V to 6.2V .

The encoder signal is also used for position determination. It is processed by microcontroller using the counter module, therefore allowing the exact angle of position to be determined. This signal is then converted from digital to analog form using digital to analog converter. Movement range from -60° to +60° corresponds to voltage levels from -4,98V to 4,98V, respectively.

IV. VIRTUAL MODEL OF HAPTIC PADDLE AND ENVIRONMENTS

In order to provide visual feedback and implement bilateral control, virtual reality haptic paddle had to be designed. Haptic paddle was placed in different virtual environments, which represented different configurations of two basic physical elements, spring and damper. One additional environment in which haptic paddle was placed between two walls, was also designed for the purpose of this paper. Four environments in total were designed and tested, as will be presented below. The 3D models were made using 3DS MAX software package.

A. Environment I

First environment consists of two solid walls, with haptic paddle placed between them, as shown in Fig. 5. Walls are positioned in a plane orthogonal to haptic device stand, and also orthogonal to the plane of rotation of the haptic paddle. The paddle in central position is equally distanced from both walls. In order to reach the point of contact with one or another wall, the paddle has to be rotated by the angle of 40° from reference position, in mathematical positive or negative direction.

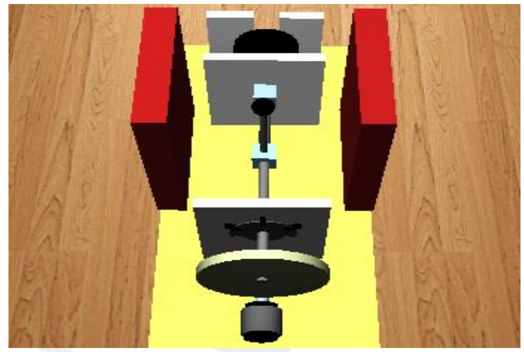

Figure 5. Virtual model of two walls environment

At the point of contact, maximum voltage is applied on the motor, so the paddle is prevented from moving through the wall. It is assumed that the walls do not compress. The voltage, applied to the motor, has the positive or negative sign, depending on the position of the paddle.

B. Environment II

The Environment II consists of the haptic paddle and a plate, which is attached to one end of four springs. The other end of the springs is attached to immobile wall. The plate and the wall are positioned in parallel planes, which are, again, orthogonal to the haptic device stand, and to the plane of rotation of haptic paddle. The plate is placed nearer to the haptic device than the springs and the wall, as shown in Fig. 6. Besides the haptic paddle, the plate and springs are also moving parts in this configuration.

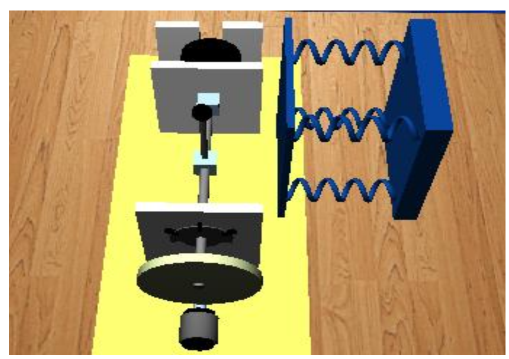

Figure 6. Virtual model of spring environment

In order to reach the plate, haptic paddle has to be rotated to an angle of 10° from reference position. Further movement towards the plate is possible, but from this point on, the amount of voltage, proportional to the position of the paddle, is applied to the motor. If the springs are compressed at any amount, the force, with direction opposite to compression, is generated. As the position of paddle is increasing above 10°, the force needed to be applied to the paddle by the operator, in order to continue with progress, is also increasing. The maximum force to the paddle is applied at limit position of the paddle, when the springs are completely compressed, and no space is left for extra movement.

C. Environment III

In third virtual environment, plate with springs is placed on both sides of the haptic device, so this setup is very similar to the previous example. The position of the plate and springs from previous example remained the same. The second plate is placed in the same distance from haptic device, only on the opposite side, as if represented the mirror image of the first one. Virtual reality haptic device with two plates and springs is shown in Fig. 7.

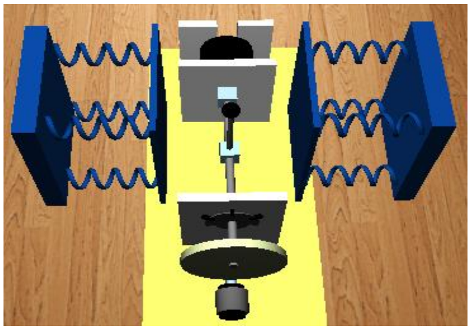

Figure 7. Virtual model of two springs environment

In order to reach one, or another plate, haptic paddle has to be rotated to an angle of 10° in positive or negative direction. The force applied by motor is proportional to paddle position, with the direction opposite of spring compression.

D. Environment IV

Fourth environment was developed in order to implement speed dependent control. As shown in Fig. 8, 3D model of haptic paddle in virtual environment is replaced with models of car and box, which are able to move along one axis. Car is controlled by a haptic paddle. Its position is directly proportional to the position of the paddle. In this experiment, the friction force was simulated, while moving the car. The force, with the direction opposite to direction of movement of paddle, is applied in form of constant voltage on the motor. The sign of voltage is changed every time the operator changes the direction of the movement of the paddle. The operator should, thus, feel constant resistance from the paddle, while moving the car.

Car is able to push the box, as soon as the contact between them has been made. While pushing the box, operator should feel the resistance which is proportional to the speed of haptic device. Higher the speed, higher the amount of voltage is applied to the motor.

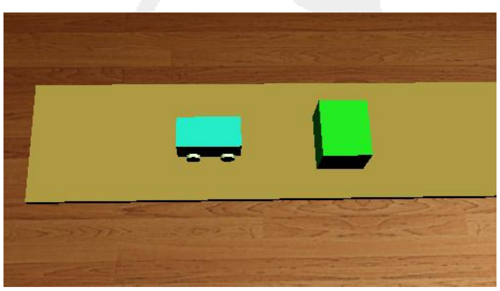

Figure 8. Virtual model of two boxes environment

V. Fuzzy Modeling of Virtual Environments

Traditional modeling is based on mathematical model of environments. Based on expert knowledge and experience, control implementation can be simplified, and it can be achieved without complex mathematical modeling using fuzzy logic [8][9]. Fuzzy controllers for previously described virtual environments were designed using Matlab/Simulink. Speed and position of mechanical haptic paddle model are used as inputs for created fuzzy controllers which provide interaction feedback from virtual environments. Position was used as an input of fuzzy controller for Environments I, II and III, while, speed was used as an input of fuzzy controller for Environment IV. Simulink model for Environments I, II and III is shown in Fig. 9.

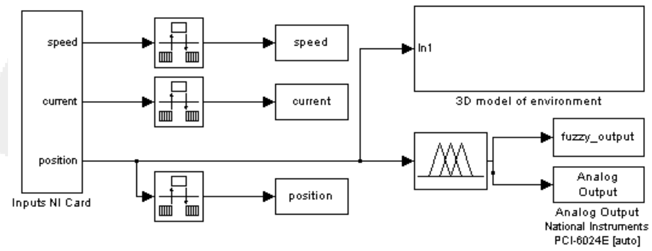

Figure 9. Simulink model for Environments I, II and III

A. Environment I

Sugeno fuzzy controller was created for Environment I. Properties of Sugeno type controller are given in Table I. Chosen input membership functions for position and chosen output membership functions are shown in Fig. 10. Output is a voltage of DC motor.

Table I. FIS (Fuzzy Inference System) Parameters

FIS TYPE	Sugeno
AND method	prod
OR method	probor
Defuzzyfication	wtaver

The final output of the system is the weighted average of all rule outputs, computed as

$$FINAL\ OUTPUT = \frac{\sum_{i=1}^{N} w_i z_i}{\sum_{i=1}^{N} w_i} \tag{4}$$

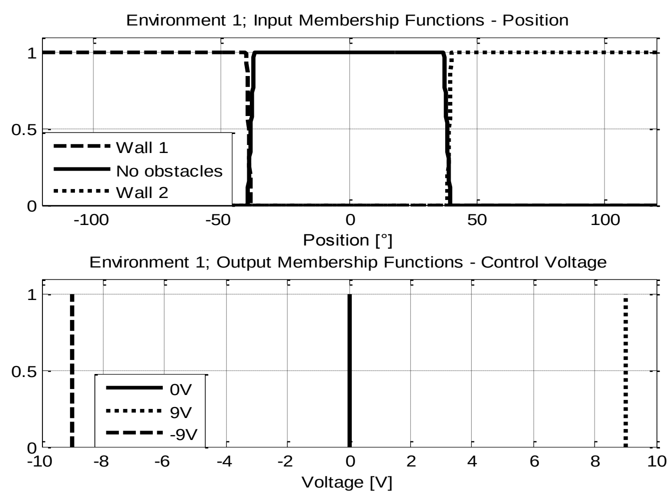

Figure 10. Environment I; Membership Functions

where N is the number of rules [9]. In this case the number of rules N is 3. These rules are shown in Table II.

TABLE II. RULE BASE ENVIRONMENT 1 FUZZY CONTROLLER

If Position is Wall 1	Output voltage is -9V
If Position is No Obstacles	Output voltage is 0V
If Position is Wall 2	Output voltage is 9V

B. Environment II

Mamdani controller for Environment II was designed. Properties of Mamdani type controller are given in Table III.

TABLE III. FIS (FUZZY INFERENCE SYSTEM) PARAMETERS

FIS TYPE	Mamdani
AND method	min
OR method	max
Implication	min
Aggregation	max
Defuzzyfication	centroid

Chosen input memberships functions for and chosen output membership functions are shown in Fig. 11. Centroid of Area (5) is used as defuzzification strategy.

$$FINAL\ OUTPUT = \frac{\int_z \mu_A(z) z dz}{\int_z \mu_A(z) dz} \qquad (5)$$

where $\mu_A(z)$ is the aggregated output of membership function, and $\int$ denotes the union of (z, μ(z)) pairs. Fuzzy rules are shown in Table IV.

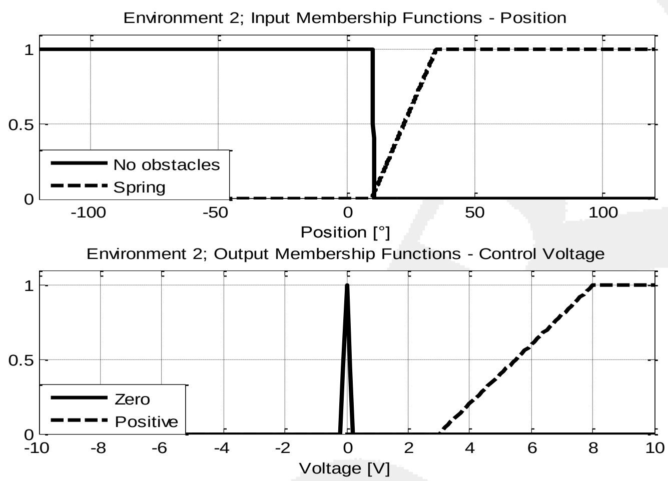

Figure 11. Environment II; Output Membership Functions

TABLE IV. RULE BASE ENVIRONMENT 2 FUZZY CONTROLLER

If Position is No Obstacles	Output is Z
If Position is Spring	Output is S

C. Environment III

Mamdani controller was also used for describing Environment III. FIS parameters are the same as for Environment II and are shown in Table III. Chosen input membership functions for position and output membership functions are shown in Fig. 12.

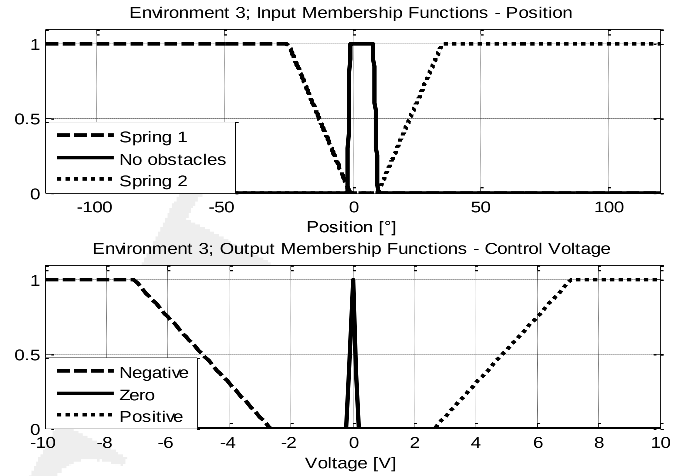

Figure 12. Environment III; Membership Functions

Centroid of Area (5) is used as defuzzification strategy. Fuzzy rules for this controller are shown in Table V.

TABLE V. RULE BASE ENVIRONMENT 3 FUZZY CONTROLLER

If Position is No Obstacles	Output is Z
If Position is Spring 1	Output is S1
If Position is Spring 2	Output is S2

D. Environment IV

Position and speed are used for describing Environment IV and that is why Simulink model for this environment is different from others, as shown in Figure 12.

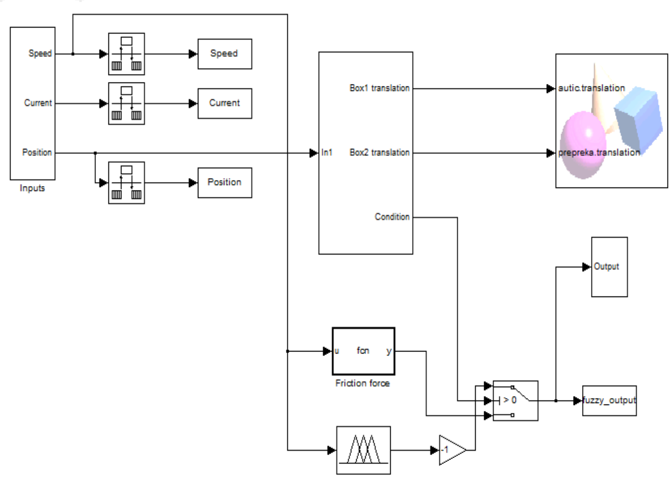

Figure 13. Simulink model for Environments IV

Fuzzy controller for this environment uses speed as an input. Mamdani type of controller was also used and FIS parameters are shown in Table III. Chosen input membership functions for speed and chosen output membership functions are shown in Fig. 14. Centroid of Area (5) is used as defuzzification strategy. Fuzzy rules for this controller are shown in Table VI.

TABLE VI. RULE BASE ENVIRONMENT 4 FUZZY CONTROLLER

If Position is No Obstacles	Output is Z
If Position is Spring 1	Output is S1

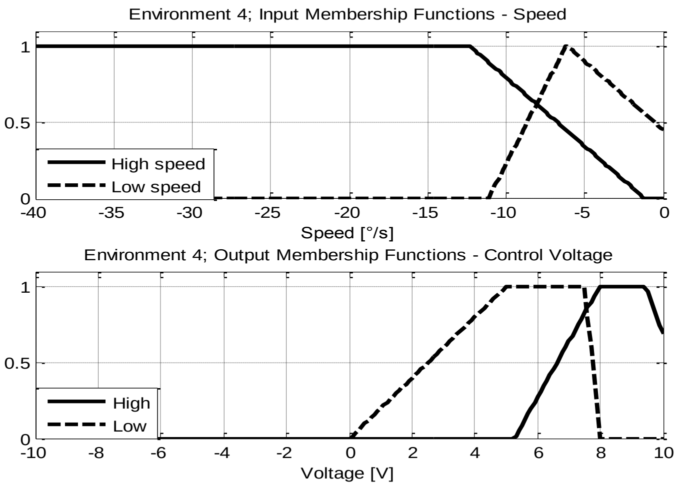

Figure 14. Environment IV; Membership Functions

TABLE VI. RULE BASE ENVIRONMENT 4 FUZZY CONTROLLER

If Position is No Obstacles	Output is Z
If Position is Spring 1	Output is S1

VI. EXPERIMENTAL RESULTS

Each virtual environment has been tested using created electromechanical model (Fig. 2). For demonstration of fuzzy controller effectiveness, measured data were collected for each experiment and they are shown for each environment.

A. Environment I

Experimental results for Environment I are given in Fig. 15.

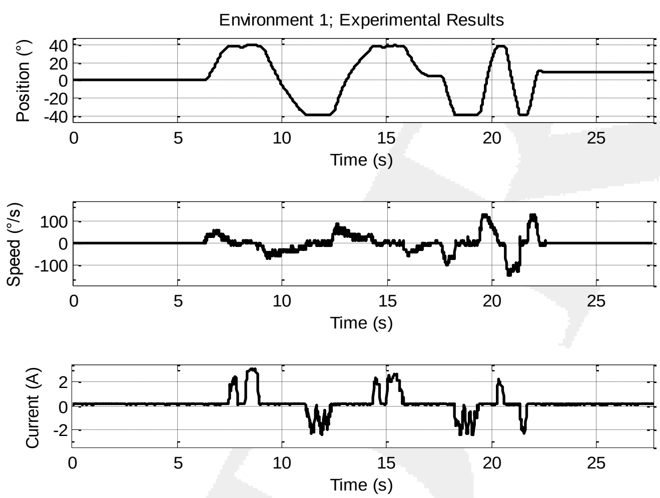

Figure 15. Environment 1; Experimental Results

As it can be seen in previous figure, operator made few movements which included touching the walls in Environment I. The diagram shows that the motor was providing resistance during this contacts and did not allow operator to "pass through the wall".

B. Environment II

Experimental results for Environment II are given in Fig. 16.

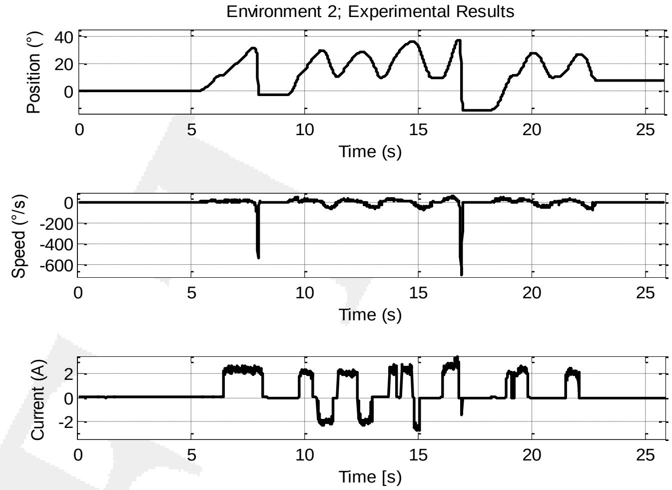

Figure 16. Environment 2; Experimental Results

Like in the previous experiment, operator made few movements that are demonstrating behavior of spring in this virtual environment. By observing the experimental results it can be noticed that motor was providing opposite force to the spring compression. The peak changes in speed are generated by opposing force to spring compression.

C. Environment III

Environment II consists of two springs as previously described. Operator pulled paddle compressing one of the springs and then released it. This generated continued movement of paddle in opposite direction which was caused by force exerted by spring. Environment was designed so the paddle can reach area of second spring if first one is compressed enough. This can be seen in experimental results for this environment given in Fig. 17. This caused high speeds of paddle.

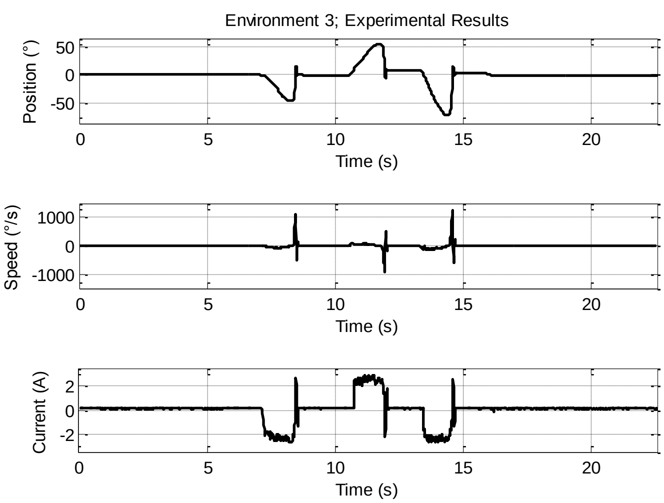

Figure 17. Environment 3; Experimental Results

D. Environment IV

While testing the Environment IV, operator made few movements of paddle which included pushing the second box. This caused higher resistance and oscillations of speed and current.

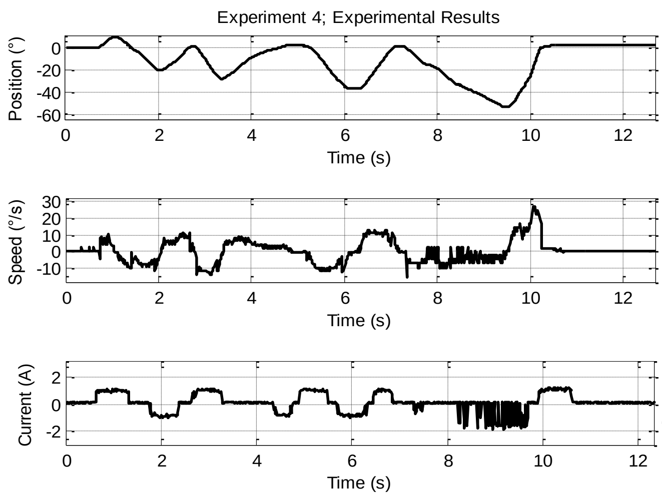

Figure 18. Environment 4; Experimental Results

By observing the experimental results shown in Fig. 22 it can be noticed that motor provided resistance during movement of box.

VII. Conclusion

The suggested low-cost solution of haptic paddle control system proved its functionality throughout the different experiments it was subjected to. The position and speed based fuzzy logic control represents an easy-to-implement control algorithm without narrowing the area of possible utilization of complete system.

Nevertheless, the main purpose of this system is to be used as a didactic tool therefore bridging the gap between theory and practice and making the understanding of bilateral control concepts easier for students. Besides this, it can easily be used as a platform for developing and testing of other control algorithms, as for the development of new and different virtual environments.

Since current output signal is provided, the future work may include the implementation of force observer. Different kind of control could be implemented and compared with fuzzy control for existing virtual environments as well as for new virtual environments. More electromechanical models can be made and they can be used for implementation of bilateral control. Also, future work may include implementation of cascade regulation, real-time delay compensation etc.

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