Haptic Interface Controller Design using Intelligent Techniques

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ABSTRACT:
Haptic technology has enormous applications in several fields from medical, military, and in our day-to-day life's products including video games, smartphones, and smart cities. The Haptic Interface Controller (HIC), a key circuitry for interaction between the user and the virtual world, has two main control issues: stability and transparency. These two issues are complementary to each other i.e. emphasis on one will degrade the other and vice-versa. To address this, intelligent control techniques including Genetic Algorithm (GA), Feed-Forward Neural Network (FFNN), and Fuzzy Logic Control (FLC) have been used in design of the HIC. To ensure the performance in real-time, in system parametric uncertainty and delay have been added while designing the HIC so that a balance could be maintained between the two issues.

KEYWORDS: Genetic Algorithm, Neural Network, Fuzzy Logic Control, Haptic Interface Controller, Stability, Transparency.

1. INTRODUCTION

A haptic device basically is a two-port device that connects the user and the Virtual Environment (VE). It is the combination of a robotic manipulator, interface circuitry and the VE. Here, the user applies the force input using a manipulator and visualizes the same executing in the virtual environment and the force or velocity generated in VE is sent back to the user by means of haptic device. The amount of force applied by the user for the VE must be reached to VE and vice-versa. This force is affected by the various disturbances which can be compensated and overcome by the use of a suitable interface controller for the device named as Haptic Interface Controller (HIC) [1].

In the haptic system, there is two major performance concern: stability and transparency. Stability here means that for the defined input or feedback signal the system response must settle over a certain period of time and should not vibrate/oscillate. Transparency means the amount of signal provided by the user that must be executed in VE with minimum loss in the minimum period of time and vice-versa. Both of these parameters must be achieved for a realistic feel of touch [2], [3].

In case of haptic system, transparency and stability are complementary to each other. Hence when we try to maintain the stability using the HIC parameters, the transparency gets reduced and vice-versa [2], [4]. So the selection of HIC parameter is required to overcome this. Hence for the optimal selection of interface controller parameters, intelligent control techniques may be employed.

Stability issues discussed in [5] are overcome in [6] by Weir et. al using the passivity approach. Gil et al used R-H method to define the range of stability with interface parameters and proposed parameter range for LHIfam device [1] but uncertainty has not been considered by the author. Moreover, for maximum stability in a real-time environment, one has to consider various factors affecting the performance such as parametric uncertainty and delay. A system has to be designed considering the above-said factor and design of the HIC. The selection of these parameters using various classical techniques is presented in [4]. This method has shown good results but the selection of parameters of HIC has been always a challenging task. Here, intelligent techniques come into play to find the optimal solution ensuring transparency while preserving the stability of the system. Various intelligent control techniques are existing in the literature such as Genetic Algorithm (GA), Particle Swarm Optimization (PSO),

Fuzzy Logic Controller (FLC), and Neural Network. These intelligent techniques have various advantage as well as disadvantage over classical one. Genetic algorithm is the heuristic search method largely used by optimal solutions. Neural network has calibre to perform in uncertain environment but it requires system initial training effectively. FLC involves various linguistic control strategy conversion based on expert knowledge to automatic control [7–12].

In this paper, intelligent techniques have been used to find the optimal parameters of Haptic Interface Controller (HIC) for haptic system. The organization of this paper is as follows: haptic system modelling is defined in section II, HIC design using Genetic Algorithm (GA), Feed-Forward Neural Network (FFNN) and Fuzzy Logic Controller (FLC) are given in sections III, IV and V respectively. The result comparison and discussion is presented in sections VI and conclusion is followed in section VII.

2. HAPTIC SYSTEM MODELING

The haptic system has three major sections: a robotic manipulator, interface circuitry and virtual environment (VE) as shown in Fig. 1. The user interacts with the haptic device with the help of a manipulator. It generates the input signal for the VE. This signal gets enhanced and controlled through the interface controller and executed in VE. The Laplace transform of the haptic model as transfer function $P(s)$ can be written as

$$P(s) = \frac{X(s)}{F(s)} = \frac{1}{ms^2 + bs} = \frac{1}{s(ms+b)} \tag{1}$$

Where, m is the mass coefficient and b is a damping coefficient of the haptic system [1], [2].
The transfer function of $C(s)$ of haptic interface controller (HIC) is chosen as

$$C(s) = K + \frac{B}{s} \tag{2}$$

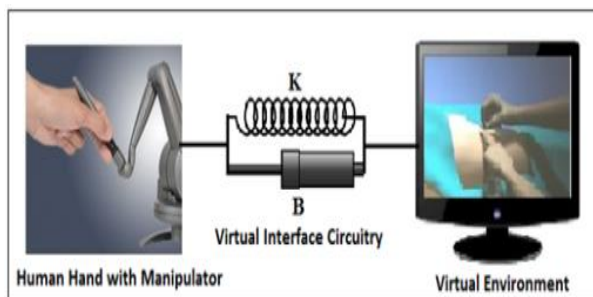Where, K and B are virtual stiffness and virtual damping respectively.

Fig. 1. Haptic system interface model.

To realize the haptic system model, the model uncertainty is introduced as transfer function $W(s)$ as (3)

$$W(s) = \psi ms + \Omega b \tag{3}$$

Where, Ω and ψ are constants.
The block diagram of haptic system having fixed user force as input, haptic model having uncertainty as $W(s)$, interface circuitry controller $C(s)$, delay and zero order hold (ZOH) is shown in Fig. 2. To incorporate the various level of uncertainty, $'\Delta'$ is included as varying between $-1 \leq \Delta \leq 1$ [13].
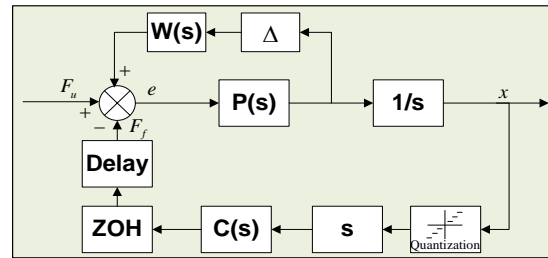

Fig. 2. Haptic system model with uncertainty and delay.

The objective is to optimally design the HIC. K and B are to be selected so that stability is preserved while increasing the transparency in presence of uncertainty and delay etc.

3. HAPTIC INTERFACE CONTROLLER USING GENETIC ALGORITHM

Genetic Algorithms (GA) are meta-heuristic algorithms inspired by natural selection process. In this algorithm, an objective function or fitness function is assigned to every individual. Using this objective function, the fitness of an individual is evaluated and further survival of the fittest theory is applied. GA has three main stages, known as reproduction, crossover, and mutation [14], [15].

3.1. Selection of Fitness Function HIC

To minimize the error signal $e(t)$, the Integral of Time Absolute Error (ITAE) function is considered as the most sensitive in literature [16], [17]. This function is chosen in this paper for the calculation of fitness function. The ITAE function is given as

$$ITAE = \int_0^\infty t * |e(t)| dt. \tag{4}$$

The system considered for this simulation experiment incorporates the uncertainty and delay. Using GA, the gain parameters of HIC K and B obtained, are given in Table 1.

From this simulation experiment, obtained force error signal $e(t)$ and feedback force $F_f(t)$ are shown in the Figs. 3 and 4 respectively. It is observed that after initial transient period, these two parameters settle to their desired values.
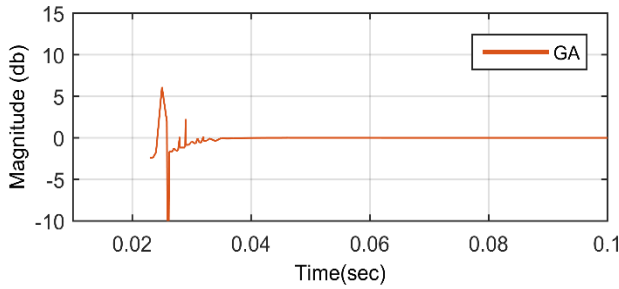
Fig. 3. GA-PI controller error response *e(t)* with uncertainty and delay.
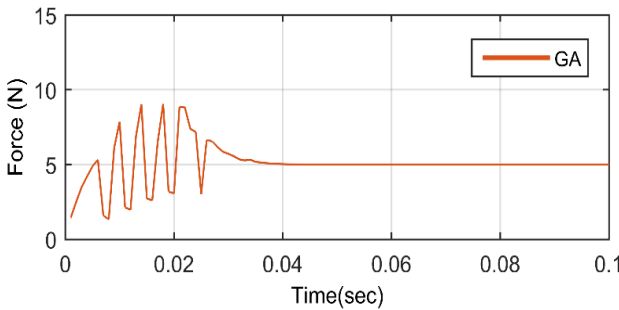

Fig. 4. GA-PI controller feedback force response with uncertainty and delay.

The settling time for force error *e(t)* is obtained as 37ms as can be seen in Fig. 3.

4. HAPTIC INTERFACE CONTROLLER (HIC) DESIGN USING NEURAL NETWORK

The neurons are the combination of activation function and the summing node, whereas the neural network is the interconnection between the neurons. The common structure of the neural network is shown in Fig. 5. Different neurons are linked together using weight function. These weight functions are selected based upon the training method. Weights are used to connect neurons. The weight matrix of NN can be adjusted using various techniques [18].

In NN, *m* number of input are connected to *n* neurons [18]. The input vector '*x*' and weight matrix have been shown in (5) and (6) respectively.

$$x = [x_1\ x_2\ x_3 \dots \dots x_m]^T \tag{5}$$
$$w = [w_1, w_2, w_3, \dots w_m] \tag{6}$$

The y as output may be defined as transfer function *f* as

$$y = f[(x_1 w_1 + x_2 w_2 \dots \dots x_m w_m) + b] \tag{7}$$

Where, b is bias. It can be expressed as

$$y = f(x) = f[b + \sum_{k=1}^{m}(x_k w_k)] \tag{8}$$

The output vector 'y' may be defined as

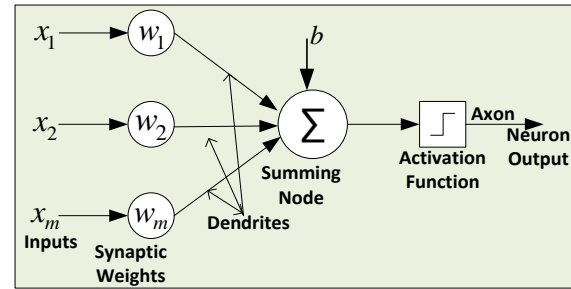$$y = [y_1\ y_2\ y_3 \dots \dots y_n]^T \tag{9}$$

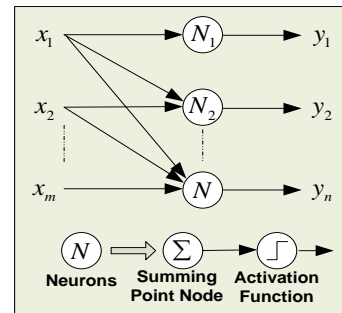**Fig. 5.** Structure of Artificial Neurons.

Fig. 6. Architecture of Neurons.

In [4], the authors have selected the HIC parameters using the manual tuning method. In this paper, *K* is set to 1000 and *B* has been tuned using NN. The hidden layer and number of neurons are selected based on literature. The NN of single hidden type is used to take smaller computational time and good performance whereas multilayer model is used for complex system. In present system, single layer NN model has been selected [19]–[21]. This NN model has been trained using training data obtained from the applicable of ZN method.

The NN algorithm for haptic system is presented as follows.
Step 1: Generate the training for NN for force error *e(t)* as input and for control signal as output.
Step 2: Train the NN using training data with FFNN.
Step 3: Initialize the NN and simulate the haptic system model using FFNN parameters.
Step 4: Save the obtained control parameter and the force error.
Step 5: Repeat step 3 to 4 until stopping criterion achieved.
Step 6: Select the interface parameters with the least force error.
Step 7: Simulate the system model using obtained optimal parameters.

Table 1. NN Parameters for HIC design.

Number of Weight Elements	10
Number of Inputs	1
Number of Layers	2
Number of Output	1
Transfer Function	Traingda
Activation Function	tansig

The simulation study is performed with $K = 10.5$ and $B = 1000$ as obtained from the NN for HIC design. The force error $e(t)$ and feedback force $F(t)$ responses are shown in Figs. 7 and 8 respectively obtained from this simulation study.
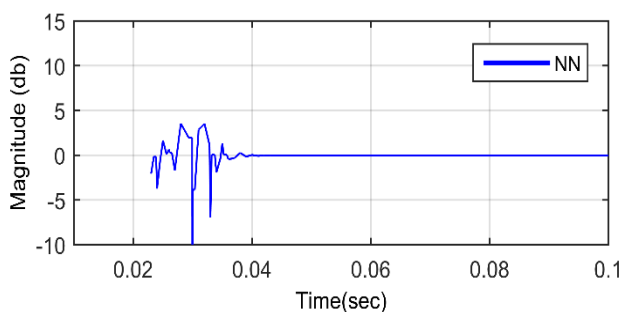

Fig. 7. HIC error response $e(t)$ using FFNN.
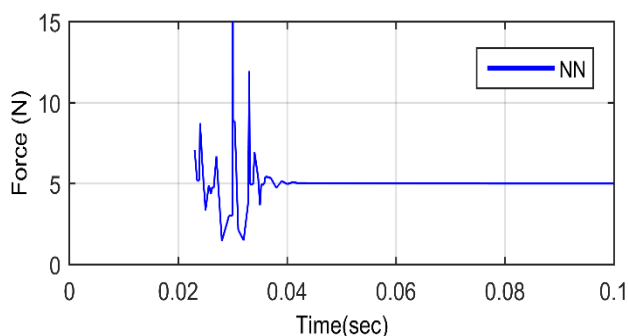

Fig. 8. HIC feedback force response using FFNN.

The settling time obtained using NN for force error $e(t)$ response is 38ms. It has been observed that the settling time parameter has been reduced significantly compared to the conventional ZN method where settling time was 60ms [4].

5. FUZZY LOGIC CONTROL
In this section, HIC has been designed using Fuzzy Logic Controller (FLC). FLC is the most significantly used technique for finding the solution which uses human expertise and experience to design a controller. It uses If-Then rule to select various conditions for HIC design. FLC design has various advantages over other control techniques such as robust, customizable, emulate

human deductive thinking, reliable and efficient. In fuzzy, there are basically six assumptions. These are: the plant is controllable and observable, existing knowledge of plant, the existence of a solution, a 'good enough' solution is enough, range of precision and issue regarding stability. The major component of FLC is fuzzifier, defuzzifier fuzzy, rule base, fuzzy knowledge base and inference engine [22]. The system block diagram model for fuzzy is shown in Fig. 9.
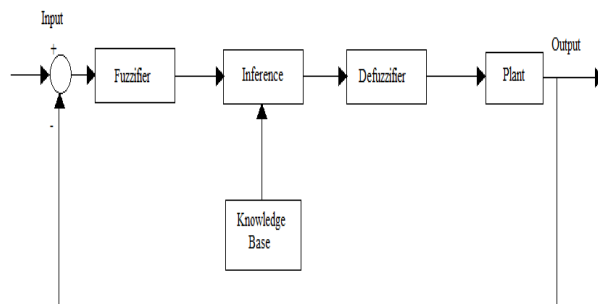

Fig. 9. Fuzzy Logic Controller (FLC) system block diagram.

First of all, a rule-based is designed using If-Then rules, then membership function and fuzzy set rule are defined in the database. The fuzzification converts the state variable of the system into a crisp fuzzy quantity. There are two major challenges in FLC design. One is to choose membership function shape and the other is fuzzy if-then rule base. The Fuzzy Inference System (FIS) includes a fuzzy rule base and membership function. The most common FIS used are the Mamdani and Sugeno inference system. Decision-making logic is used to generate output. The input fuzzy sets and knowledge base are used to make the decision making. The results corresponding is then de-fuzzified using defuzzification strategies. The commonly used strategy is the mean of maximum, maximum criterion, and centroid methods.

5.1. Self-Tuned Fuzzy tuned HIC controller
In this section, a self-tuned FLC has been designed for the haptic system whose parameters and system condition change with time. Moreover, the optimal parameters of controller are required to be found to maintain the balance between transparency and stability. The error $e(t)$ and derivative of error $\dot{e}(t)$ are contributed as input to the FLC. For the input function of error and derivative of error, five overlapping sets are chosen as: Positive Large (PL), Positive Medium (PM), Zero (ZE), Negative Medium (NM), Negative Large (NL). The output set for K and B are chosen As Positive Very Large (PVL), Positive Large (PL), Positive Medium-Large (PML), Positive Middle (PM), Positive Middle Small (PMS), Positive Small (PS), Positive Very Small (PVS). The 25 fuzzy rule set are executed by FIS

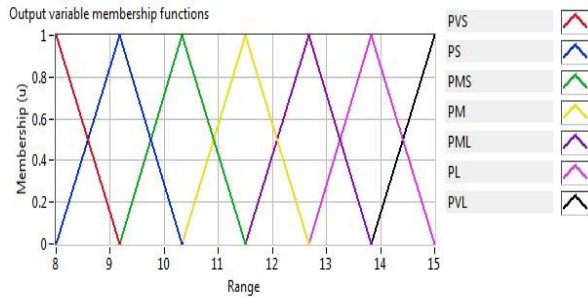for obtained output, and these are shown in the following figures respectively.

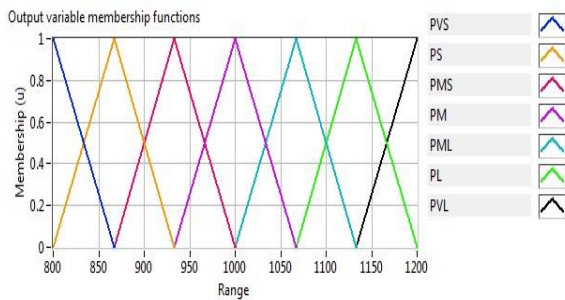**Fig. 10.** Output membership functions for virtual stiffness K.

Fig. 11. Output membership functions for virtual damping B.

Rule base for the virtual stiffness K are given in Table 3 and for virtual damping, B are given in Table 4.

Table 2. Rule Base For Virtual Stiffness K.

$\dot{e}$ \ e	PL	PM	ZE	NM	NL
PL	PVL	PVL	PVL	PVL	PVL
PM	PM	PM	PML	PML	PML
ZE	PMS	PMS	PS	PVS	PVS
NM	PML	PML	PML	PML	PML
NL	PVL	PVL	PVL	PVL	PVL

Table 3. Rule Base For Virtual Damping B.

$\dot{e}$ \ e	PL	PM	ZE	NM	NL
PL	PM	PM	PM	PM	PM
PM	PMS	PMS	PMS	PMS	PMS
ZE	PS	PS	PVS	PS	PS
NM	PMS	PMS	PMS	PMS	PMS
NL	PM	PM	PM	PM	PM

The HIC parameters obtained by self-tuning FLC are employed in the simulation experiment and the obtained force error $e(t)$ and feedback force $F(t)$ are shown in Figs. 12 and 13, respectively.
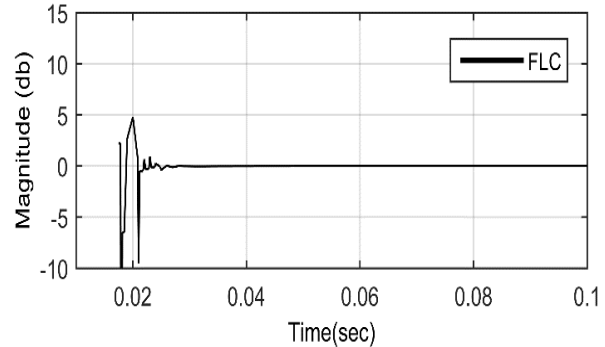

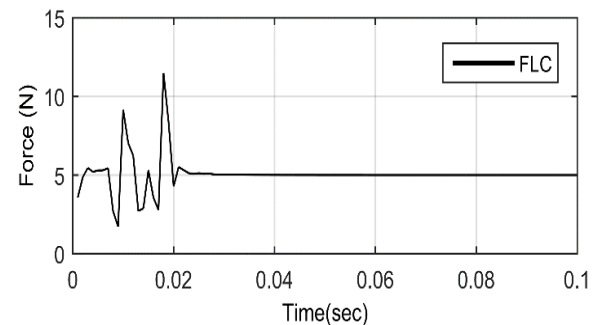**Fig. 12.** Force error $e(t)$ response using FLC.

Fig. 13. Feedback force F_f response using FLC.

The settling time for force error response is 30ms in case of FLC based HIC design. This improvement further enhances the transparency of system preserving the stability. After some initial transient, both the signals settles down near their desired values respectively.

6. RESULT ANALYSIS

In this section, the performance is obtained with implemented intelligent techniques i.e. GA, NN, and FLC are compared with conventional method of ZN. The corresponding force error $e(t)$ and feedback force $F(t)$ responses are shown in Figs. 14 and 15, respectively.
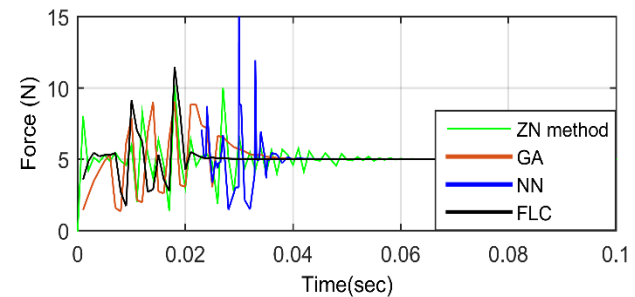

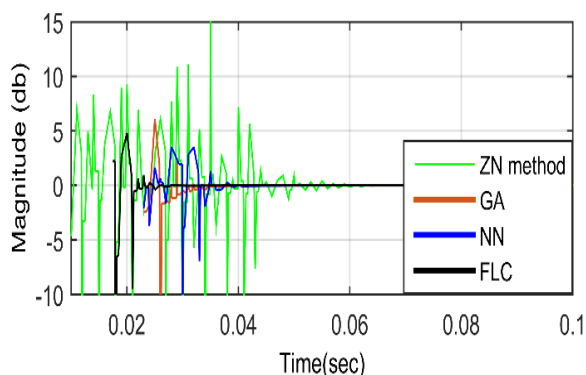**Fig. 14.** Force error $e(t)$ responses using various techniques.

Fig. 15. Feedback force F_f responses using various techniques.

These responses show that FLC control technique gives better results compared to other intelligent and conventional ZN methods in terms of settling time and initial oscillations. The HIC parameters for haptic system and different performance measures obtained using various intelligent methods are tabulated in Tables 5 and 6, respectively.

Table 4. HIC Design Parameters using Different Methods.

Controller method / Parameters	ZN method	GA	NN	FLC
Virtual stiffness (K)	17	3.0083	10.5	11.2
Virtual damping (B)	800	301.8379	1000	99.5

Table 5. Performace Measure using Different Methods.

Performance Measure	Design methods			
	ZN method	GA	NN	FLC
Settling Time (ms)	60	37	38	30
Peak Overshot	21	6	4	4
Mean (abs(e))	0.2282	0.0070	0.0183	0.0154
2-Norm of Error $e(t)$	151.9880	23.7219	82.4901	63.2441

The HIC design parameters using various intelligent techniques is shown in the table. Using these parameters, performance of HIC is measured at various parameters given in Table 6. It has been observed using this table that FLC has shown least settling time compared to others. There is a significant improvement in minimization of settling time. For better analysis, the bar graph has been shown in Fig. 16 and percentage improvement in Fig. 17.
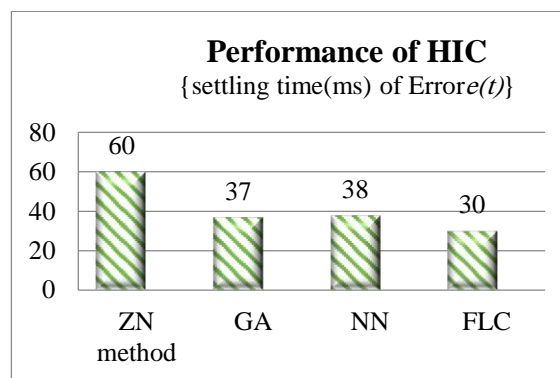

Fig. 16. Performance of HIC in terms of error setting time.
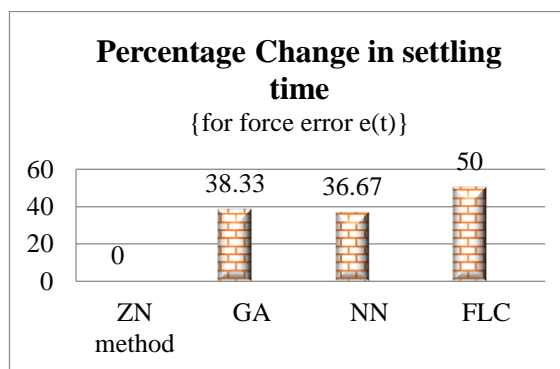

Fig. 17. Percentage improvement in settling time of $e(t)$.

Further, the 2-norms of error $e(t)$ analysis of various techniques (GA, NN and FLC) are compared in Fig. 18 with the conventional ZN method.
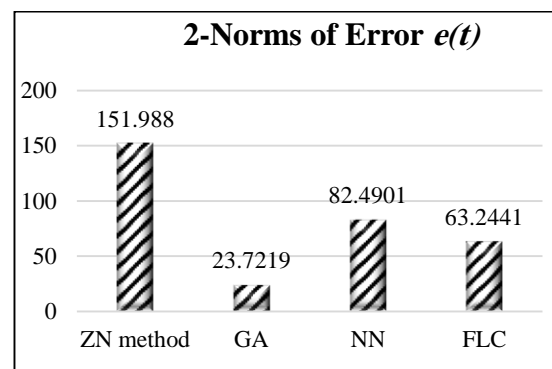

Fig. 18. Performance of HIC in terms of 2 Norms of error of $e(t)$.

The comparison analysis shows that intelligent techniques have minimized the 2 norms of force error $e(t)$ compared to the conventional ZN method. Here, GA performs better among all techniques. Peak overshoot and mean of absolute analysis for force error response $e(t)$ has been compared in Figs. 19 and 20, respectively
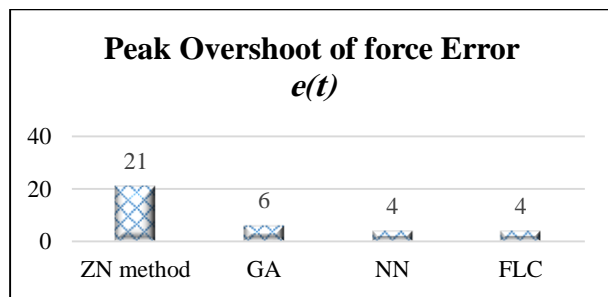
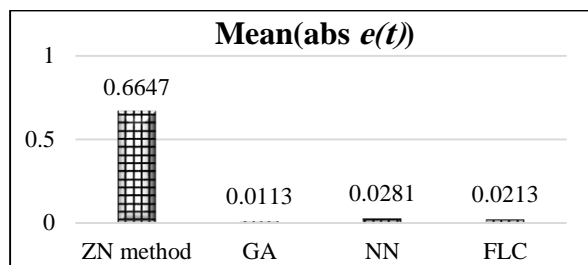**Fig. 19.** Performance of HIC in terms of Peak Overshoot of *e(t)*.

Fig. 20. Performance of HIC in terms of means of absolute of e(t).

It has been observed from the various time-domain analysis i.e. settling time, 2 norms of error and peak overshoot of force error response that HIC design using intelligent technique (GA, NN, and FLC) perform better as compared to conventional ZN method. Further among intelligent techniques, FLC outperforms other intelligent techniques in most of the parameters measure shown in Figs. 14 to 19 and tabulated in Table 6.

7. CONCLUSION

This paper presents the design of a haptic interface controller for the haptic systems. Stability and transparency are the key issues observed. Various factors affecting transparency and stability, such as delay and uncertainty, are incorporated into the system while designing the controller. Stability and transparency are inversely dependent in such a manner that enhancing one will decrease the other. So, in this paper, an optimal HIC has been designed using the various intelligent techniques *i.e.* GA, NN, and FLC, and are compared. It has been observed from the comparison that FLC designed HIC better as compared to other methods for haptic system and settling time is also reduced to half as compared to the conventional ZN method designed HIC.

8. ACKNOWLEDGMENT

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