Development of Self -Tuning Fuzzy Iterative Learning Control for Controlling a Mechatronic System

Osama Elshazly, Mohammad El-Bardini, and Nabila M. El-Rabaie

***Abstract*—In this paper, a self-tuning fuzzy iterative learning control algorithm is proposed to ensure the improvement and enhancement in the performance of the control system by using the benefits of both feedback control due to fuzzy controller and feedforward compensation due to iterative learning controller (ILC) merged in the same control system structure. The performance of proposed algorithm was assessed in a mechatronic system to illustrate the validation of the proposed procedure and the effectiveness of the self-tuning fuzzy iterative learning controller. The simulations results show that the proposed self-tuning fuzzy iterative learning control (STFILC) can reduce the trajectory error in far less number of iterations.**

***Index Terms*—Iterative learning control (ILC), fuzzy control system, self-tuning, *X-Y* table, computer numerical controlled (CNC) machines.**

I. Introduction

Most industrial systems and machines perform their tasks repetitive in nature. Such industrial systems include robots, motors, steel mills, hard-disk drives, and more generally, the class of tracking systems such as X-Y table in CNC machines. These systems are required to carry out tasks with high precision and high speeds subject to modeling variations, disturbances and repeatability imperfections [1]. Higher quality of their performance in accuracy and efficiency can enhance product quality, increase productivity, improve efficiency, and reduce costs.

The motivation that makes learning control system to be strengthened is that the control systems become efficient by learning how to fulfill the main control aims expressed as high-performance indices in desired or reference tracking and regulation with respect to load disturbance inputs [2].

During the last twenty years, a great number of ILC algorithms have been developed. ILC has become a framework including many varieties of control approach. Each one has its merits in terms of performance such as convergence, robustness, learning speed, or suitability for special plants [3], [4], [5].The main reason why ILC has attracted considerable research efforts is its simplicity, potential effectiveness, and less information about the system to be controlled is needed [6].

Due to the increase in performance requirements and complexity of tasks and processes, the modern day controllers are becoming more and more complex. On the other hand, human operators require to perform complex control tasks with good results, apparently without difficulty and without knowing the mathematical model of the system. In an era where systems and their models are getting more and more complex or may be not available, the difficulties faces the controller designers are increased, simpler controller with similar performance are always welcomed. Fuzzy logic control is the technology that can convert human thinking or knowledge into controller design [7], [8], [9]. In 1973 Zadeh published a paper [10] which established the foundation for fuzzy control. Since then fuzzy controllers have found many successful industrial applications, have shown significant improvements in system performance and have proved to be more robust than conventional controllers [11]. The main advantage of the fuzzy approach lies in the fact that the notion of the fuzzy set theory helps to implement the operator's experiences and heuristics on a controller.

Fuzzy control that evolves from heuristic knowledge has increasingly been used in recent years as an alternative to the classical PID control. The robustness to noise, model uncertainties, system parameters changes, and excellent transient performance are the advantages that fuzzy control have. However, both classical and fuzzy control cannot make the tracking error arbitrarily small. ILC is an approach that can be introduced to overcome the drawbacks of both classical and fuzzy controllers [12].

The combination of fuzzy control and the ILC scheme is aimed to improve the performance indices of fuzzy control system by alleviation of the disadvantages and make use of the advantages of both ILC and fuzzy controllers by using feedback control and feedforward compensation benefits [13].

In this paper, we propose a self-tuning fuzzy iterative learning controller that make use of fuzzy logic control to enhance the performance of the ILC scheme for controlling an *X-Y* table. In this scheme, a fuzzy system is used to update the ILC scheme parameters to be self-tuned and can be changed according to the changes in the system dynamics.

The reset of this paper is organized as follows. Some notations and preliminaries on the structure of ILC scheme are presented in Section II. In Section III, CNC milling machine *X-Y* table model used for simulation is presented. In Section IV, a focus on fuzzy control with ILC algorithm, adaptation and tuning of the ILC scheme parameters using fuzzy control are presented. Section V is dedicated to the case that applies the proposed algorithm to an *X-Y* table and presents a simulation results comparison between the proposed STFILC algorithm and classical PID-type ILC for different reference inputs to show the effectiveness of the proposed algorithm. The conclusion is highlighted in Section VI.

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II. ILC NOTATIONS AND PRELIMINARIES

Iterative learning control (ILC) can be defined as a control technique that improves the performance of dynamical systems which perform the same tasks repetitively over a finite time interval. ILC emulates the human capability of learning from practice. The basic idea behind ILC is that it uses previous trial information to update and improve the control signal for the next trial in order to improve the controlled dynamical system performance and make the tracking error to be small as possible. This idea can be illustrated in Fig. 1 [14], [15].

A. *Basic ILC Algorithm.*

For a given dynamical system with input u and output y, there are some postulations for the formulation of ILC problem, that can be described as follows [15], [16]:

- The process repeatedly performs the same task that ends in a fixed duration ($T > 0$), (T: sample period)
- The desired output, $y_d(t)$ is pre-defined with $t \in [0,T]$.
- For each trail (cycle, batch, iteration, repetition) the initial states are the same. In other words, the initial states of the objective process can be set to the same point at the beginning of each iteration.
- The plant output, $y_k(t)$, is observable.

B. *PID-Type ILC Algorithm.*

The goal of ILC is to find an iterative form of learning control law such that :

$$u_{k+1} = F(u_k, e_k)$$

The tracking objective $e_k(t) \rightarrow 0$ as $k \rightarrow \infty$ is achieved .

Under the above assumptions, if the dynamical system relative degree is one, The PID-type ILC scheme derived from the original ILC scheme of the "Arimoto D- type" [4] is given by (1) and can be illustrated in the block diagram shown in Fig. 2.

$$u_{k+1}(t) = u_k(t) + \gamma e_k(t) + K_I \int_0^t e_k(\tau)d\tau + K_d \frac{d}{dt} e_k(t) \qquad (1)$$

where : $u_k(t)$ is the control signal at k^{th} iteration , $e_k(t)$ is the tracking error at k iteration that defined by $e_k(t) = y_d(t) - y_k(t)$ with $y_d(t)$ the desired output trajectory, $y_k(t)$ the actual system output at k^{th} iteration, and γ, K_I, and K_d are the PID learning gains to be designed.

This ILC scheme described by (1) work properly for system with relative degree one such that:

$$\lim_{k \to \infty} y_k(t) \rightarrow y_d(t) \qquad (2)$$

for all $t \in [0,T]$, if

$$|1 - \gamma h_1|_i < 1 \qquad (3)$$

where: h_1 is the first Markov parameter. In the state space representation (A, B, C), $h_1 = CB \neq 0$.

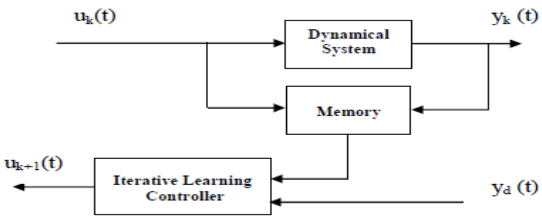

Fig. 1. Iterative learning controller configuration.

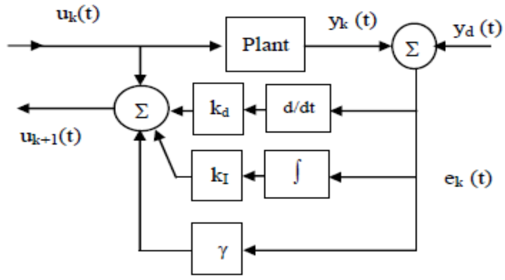

Fig. 2. Block of PID-type ILC algorithm.

III. CNC MILLING MACHINE X-Y TABLE

In most advanced manufacturing processes, two and/or three dimensional motions are in high demand for industrial applications such as parts assembly, component insertion, machining, etc. A traditional *X-Y* table often utilizes a rotary motor and couples its output shaft to mechanical translators such as gears or bears to perform linear motion, by vertical arrangement of two such linear motion implementations, two-dimensional movement is achieved. In a direct-drive system, the mechanical output is directly generated to the actuator and load and it has the characteristics of high force density, high precision and low production cost [17]. In this paper, we use a linear-drive based *X-Y* feed table of a high-speed milling machine that driven by two ETEL iron-core linear motors, one motor in the *X*-direction and the other motor in the *Y*-direction. The system dynamics can be described by two single-input single-output models. The models are obtained through frequency domain identification based on the measured frequency response functions [18]. The models that relate the control input voltage (u) to the table position (z), with $z = X$ and $z = Y$ for the X and Y axes, respectively, are of second order with a time delay T_d.

$$G(s) = \frac{z(s)}{u(s)} = \frac{B}{s(s+A)} e^{-sTd} \qquad (4)$$

IV. THE PROPOSED APPROACH (STFILC)

To derive an accurate tracking controller for a system, a fuzzy iterative learning control (FILC) method is proposed based on the rules constructed from the expert's experiences. However, the ILC with fixed learning gains suffers from the problems of slow convergence in tracking error, and sensitivity to noise and modeling uncertainty. So a fuzzy mechanism is incorporated to properly tune the learning gainsγ , K_I, and K_d to achieve fast convergent rate and enhanced robustness. The block diagram that shows the incorporation of ILC with fuzzy mechanism to obtain the self tuning fuzzy iterative learning control (STFILC) is depicted in Fig. 3.

The aim of the proposed STFILC is to remove uncertainty associated with linguistic variables, to select the learning gains according to the change in system dynamics due to unpredictable variations such that load disturbance inputs and measurements noise, and to converge with respect to given steady state error and percentage overshoot. In the proposed algorithm, we have used a PID-type ILC scheme that can be described by (1) with a fuzzy controller to build up the fuzzy controller structure with ILC described in Fig. 3. STFILC controller means that the three parameters γ, K_I, and K_d of the ILC scheme are tuned by using fuzzy tuner.

Based on the characteristic of the plant and properties of the PID-type ILC controller, the fuzzy rules can be designed. Therefore, the fuzzy reasoning of fuzzy sets of outputs is gained by aggregation operation of fuzzy sets inputs and the designed fuzzy rules. Regarding to the fuzzy structure, there are two inputs to fuzzy inference: error $e(t)$ and change of error ce(t), and three outputs for the ILC scheme parameters respectively γ, K_I, and K_d. Mamdani model is applied as structure of fuzzy inference with some modification to obtain the best value for γ, KI, and Kd. Fuzzy inference block of the controller design is shown in Fig. 4, below.

The fuzzification is solved in terms of the regularly distributed input and output membership functions for the two motors (*X*- motor and *Y*- motor) as shown in Fig. 5 and Fig. 6 respectively. The used aggregation and defuzzification methods are respectively max-min and center of area method. The Center of Area (COA) method, which is the most well-known defuzzification method and also known as centre-of-gravity method can be expressed by [9], [11], [19]:

$$U_{COA} = \frac{\sum_{i=1}^{n} \mu_i(u).u}{\sum_{i=1}^{n} \mu_i(u)} \tag{5}$$

where: U_{COA} is the crisp control value from the defuzzification process, $\mu(u)$ is the membership function grade and u is a point in the universe.

The rule base can be considered as the most important part of the fuzzy controller and it must be selected correctly to enhance the performance of the fuzzy control system [20]. The full sets of rules are summarized in table I. The linguistic variable levels used in inputs and output membership functions are assigned as (*N*) Negative, (*Z*) Zero, (*S*) Small, (*M*) Medium, and (*B*) Big .

Generally, the fuzzy rules are depending on the plant to be controlled and the type of the controller and can be extracted from the practical experience.

The proposed algorithm can be used to tune the parameters of different ILC control schemes such as P-type, D-type, PD-type, PI-type, and PID-type ILC schemes by the determination of the minimum and maximum values for these parameters to determine the universe of discourse for each parameter but operator must pay attention to make the convergence condition described by (3) is still hold in order to still achieve the stability of the controlled plant.

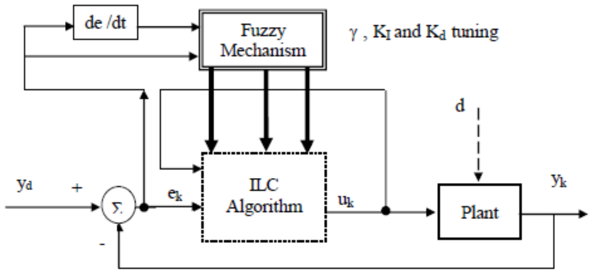

Fig. 3. Structure of self-tuning fuzzy PID-type ILC controller.

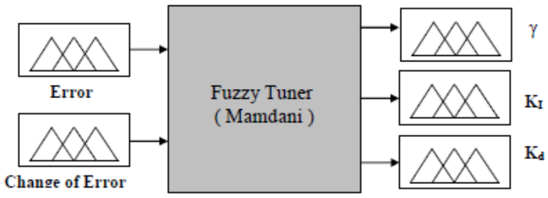

Fig. 4. Fuzzy inference block.

TABLE I: FUZZY RULES.

Ce \ e	N	Z	S	M	B
N	**B**	**N**	**S**	**M**	M
Z	**B**	**Z**	**S**	**Z**	M
S	**B**	**Z**	**M**	**M**	M
M	**B**	**S**	**M**	**M**	M
B	N	S	M	Z	M

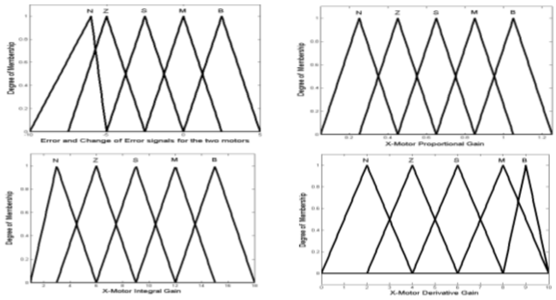

Fig. 5. *X*-motor input and output MF.

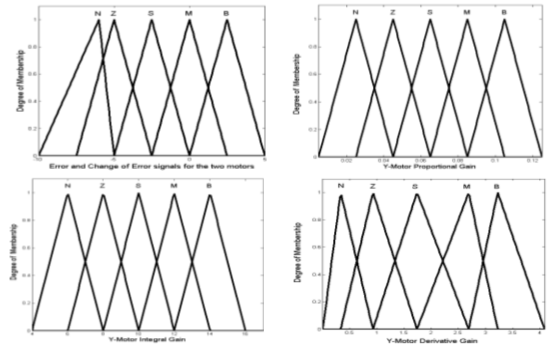

Fig. 6. *Y*-motor input and output MF.

V. SIMULATION RESULTS

In this section, simulation trials are performed using MATLAB Software to demonstrate the effectiveness of the proposed algorithm (STFILC) and the improvements in the system performance by comparing its results with the system performance using classical PID-type ILC. We apply both of the proposed algorithm and classical PID-type ILC to a linear-drive based *X-Y* feed table of a high-speed milling machine model described in Section III. Each axis is controlled independently using the same control structure with some little modification in the learning gains that differ from *X*-axis motor to Y-axis motor. The parameters of each motor are: A = 28.57 V/s, B = 4.526 m, and T_d = 0.00065 s. for the *X*-axis and A = 20.00 V/s, B = 8.916 m, and T_d = 0.00065 s for the *Y*-axis.

The nominal input voltage for each motor is 600 Volt DC [21]. The sampling period (T) used for *X*-axis motor is 0.007 s and for *Y*-axis motor is 0.01 s.

Fig. 7 shows the response and control signals of the two motors (*X* and *Y* axes) for step input using classical PID-type ILC and STFILC controllers. Where, the gains selected for the classical PID-type ILC controller are: γ =0.45, $K_I=10^{-5}$, and $K_d= 10^{-3}$. It is clear from the figure that the *X*-axis and *Y*-axis motors can track the reference input signal after some iterations using the two controllers but with better performance and no overshoot using STFILC compared to classical one that have large values of overshoot.

In order to demonstrate the effectiveness of both controllers against any load disturbance input that may affect performance of the process to be controlled, we add some disturbance of the value (d = 0.15*Reference input) for 800 iterations from iteration 200 to iteration 1000 as shown in Fig. 8. It is clear that both of the *X*-axis and *Y*-axis motors are affected by the added disturbance but after some iterations, the STFILC controller forces the systems to track the input again and there are less overshoot as compared with classical one that has large values of the overshoot.

From the above analysis of the results, the simulation results clearly illustrate the STFILC performance enhancement after some given iterations despite of adding a disturbance to the system rather than classical one.

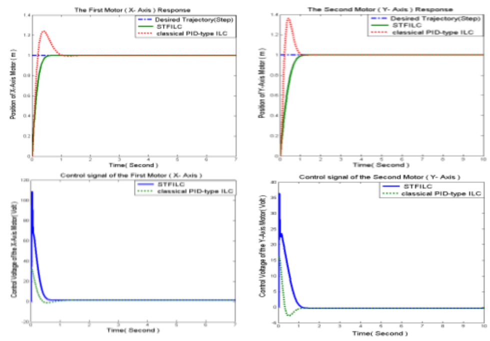

Fig. 7. The simulation results for both controllers under step change in the set point.

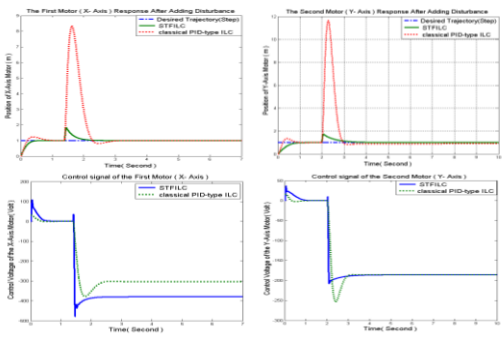

Fig. 8. The disturbance effect on the two motors.

Fig. 9 shows the response to circular contour reference input, control signals and the contour of the two motors (*X* and *Y* axes) to sine wave input for *X*-axis motor and cosine wave input for *Y*–axis motor using both controllers. These inputs can be defined by:

$$x_d = x_0 + R\sin(2\pi f t) \quad \text{and}$$
$$y_d = y_0 + R\cos(2\pi f t) \quad (6)$$

where (x_0, y_0) denotes the circle centre, R is its radius and f is the signal frequency. In the simulation environment, we have selected the center of the circle to be at the origin and the radius to be unity. It is clear that the *X*-axis motor and the *Y*-axis motor have perfect tracking for the sine wave and cosine wave reference inputs signals using STFILC rather than using classical one that indicates that there are some deviations from perfect tracking of the reference inputs signal. The results clearly illustrate the performance enhancement of the STFILC (perfect tracking) for the circular contour.

Fig. 10 shows the effect of disturbance for both types of controllers. It is clear that the classical controller can not force the system to be still track the reference input for *X* and *Y* axes motors after adding the disturbance to the system but using STFILC there are a small effect of adding disturbance to the controller performance and the proposed controller force the system to track the reference input for two motors. In other words, it is clear that the STFILC algorithm significantly improves the performance of the system better than using classical one for tracking the desired circular contour despite of adding disturbance to the system.

Finally, analytical simulation results demonstrate that the self-tuning fuzzy PID-type ILC algorithm can enhance the tracking performance significantly and it presents a good performance rather than classical PID-type ILC controller.

VI. Conclusion

A STFILC algorithm is proposed by merging fuzzy control with ILC to improve its tracking accuracy in a closed-loop dynamical process. The algorithm achieves tracking accuracy with robustness against unpredictable disturbances and perturbations. Finally, an *X-Y* table system is used as simulation example to demonstrate the proposed algorithm. Simulation results are reported to show the effectiveness and enhancement achieved by the proposed algorithm that finally reflect the good performance of the proposed algorithm rather than the classical PID-type ILC.

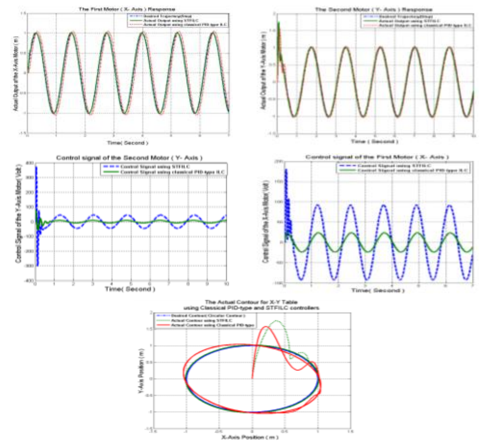

Fig. 9. The simulation results for circular contour reference input.

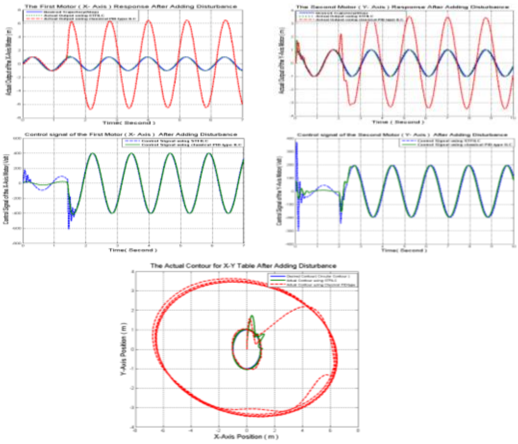

Fig. 10. The disturbance effect on X - axis and Y- axis motors.

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