INTELLIGENT CONTROLLER FOR MAGNETOSTRICTIVE MICROPOSITIONING DEVICE FOR ULTRA-PRECISION

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ABSTRACT

Generally, requirements such as high performance and small sizes for mechatronic systems, have led modern industry to design positioning systems with better characteristics of acceleration and positioning accuracy. The increasing demand for components with better metrological and finishing characteristics such as x-ray and infra-red lenses, has prompted the development of a number of types of micropositioning systems that are able to move machine elements in very small displacements with high levels of accuracy. In this work, it is proposed the use of a new type of actuator, which employs the properties of electromagnetic strain of certain metallic alloys (magnetostrictive actuators). Digital control systems that use control algorithms based on fuzzy logic (FL) and artificial neural networks (ANN) for micropositioning control are considered and their application proposed.

Key words: Micropositioning Devices, Magnetostrictive Actuators, Intelligent Control

INTRODUCTION

The fabrication of components with high form accuracy (1μm), low surface roughness (nm) and low subsurface damage such as for complex optical systems, demands the use of high precision positioning machines capable of following complex movements. Presently, this kind of components can be obtained by ultraprecision diamond turning and grinding machines.

The machine tool plays an important role in this kind of fabrication. In broad terms, to achieve adequate characteristics of positioning resolution and dynamic performance, ultraprecision machine tools must present extremely high overall structural stiffness and high dynamic performance servo mechanisms and control systems.

Ultraprecision displacement systems are not only required in machine tools but also in metrology systems and optical assembly systems. Examples of such systems are stylus and optical profilometers, optical and V.L.S.I. manufacturing systems.

This work presents the development of a type of modular architecture micropositioning system. The dynamic performance of the micropositioner, using digital control strategies based on Neural Network and Fuzzy Logic is presented and compared with results obtained by different authors. It is shown that technique permits the attenuation of instabilities and non-linearities of the

servosystem, permitting resolutions of the order of nanometres.

MICROPOSITIONING SYSTEM

Most commercial precision machine tools do not possess the required characteristics of accuracy and repeatability to machine brittle materials, correct systematic errors and possibly random errors for the fabrication of non-axysymmetric components. An additional system for the positioning and/or correction of errors is, therefore, desirable to attain the required characteristics of form, surface roughness and subsurface integrity.

Several types of device have been developed to accomplish the above. Figure 1 shows a schematic of a modular toolpost, which uses a leafspring guide system. [CAMPOS RUBIO et al, 1998].

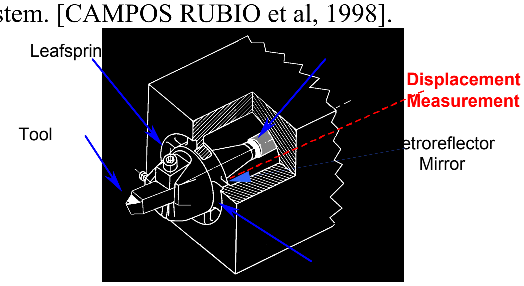

Figure 1 – Active Toolpost for Ultraprecision

The use of an appropriate drive system for positioning of precision elements is crucial. Several types of linear actuators could be mentioned here as a potential solution (e.g. hydraulic, pneumatic, fine screws, levers etc) but, in ultra-precision design, it is likely that there will be few design options for selection. In the case of ultra-fine tool displacement described in this work, solid state magnetostrictive actuators were chosen.

Magnetostrictive materials are able to transform an electric signal into linear movement within the range of a few micrometres [CAMPOS RUBIO et al, 1996]. The load carrying capacity of a magnetostrictive actuator can easily reach 1 kN and the bandwidth can be as high as several kHz. Magnetostrictive actuators are particularly suitable for fine positioning as they provide high positioning accuracy, fast time response, high stiffness and high bandwidth.

MICROPOSITIONER MODEL

The elements that make part of the dynamic system is described below using the appropriate mathematical formulation (mathematical model). Figure 2 shows the block diagram of the dynamic system.

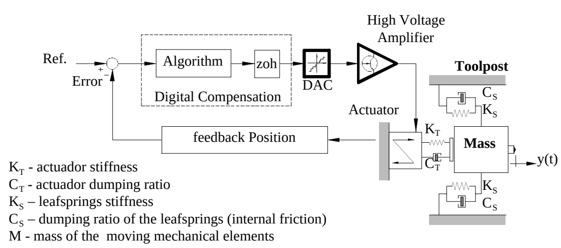

Figure 2 - Dynamic System Structure.

This system can basically be divided into two parts: The digital controller and the plant, which is composed by the remaining elements of the system (electro-mechanical system). The plant can be further divided into two distinct parts. One corresponds to the magnetostrictive actuator (MST) and the other to the moving mechanical elements.

Moving Mechanical Elements (Toolpost)

The toolpost moving mechanical elements mathematical model is shown in Equation 1 [MIRON, 1989], where ζ is the structural dumping ratio (0.08) and ϖ corresponds to the resonant frequency of the system (200 Hz) for a 650 g mass.

$$\frac{Y(s)}{X(s)} = \frac{2 \cdot \xi \cdot \varpi_c \cdot \left(s + \frac{\varpi_c}{2 \cdot \xi} \right)}{s^2 + 2 \cdot \xi \cdot s + \varpi_c^{\,2}} \qquad (1)$$

Magnetostrictive Actuator

This component converts an electrical current into a proportional displacement. The mathematical model for this type of element, according to the literature order system, where ζ is the dumping ratio and ω_n is the resonant frequency ($\omega_n = 2\pi f_r$).

An MP 50/6 Etrema Terfenol-D^R magnetoestrictive actuator was used, which has an expansion range of ±25 μm for the input signal of ±1.5 A.

$$\frac{X(s)}{I(s)} = \frac{K_{MST} \cdot \varpi_n^{\,2}}{s^2 + 2 \cdot \xi \cdot s + \varpi_n^{\,2}} \qquad (2)$$

Table 1 – System Parameters

	Mechanical Elements	MST
Freq Response. (f_r)	450 Hz	5 kHz
Stiffness (k)	5.25 10^6 N/m	7 10^6 N/m
Dumping Ratio (ζ)	0.080	0.097
Gain (K_{iii})	452.39	1.66 10^{-5} m/A

There are two regimes of operation, one for several micrometre range where the effect is strictly amplitude proportional and that below this level where the effect diminishes with reducing amplitude. The former can be readily modeled as a (fixed) attenuation and phase lag; the latter indicates that, for ultraprecision control system settling, the effect is negligible [DUDUCH, 1993].

HYBRID CONTROLLER "PI *FUZZY* + D"

Due to inertia of the moving elements, there may be a motion after the driving signal is ceased. This characteristic makes the plant control extremely difficult.

Since traditional PID controllers are not adequate when the plant parameters vary [TAO & TAUR, 1995], the inclusion of Fuzzy Logic in a traditional PID controller has the objective of reducing the overshoot and diminishing the time response. Earlier observations (e.g., CAMPOS RUBIO et al., 1996) show that:

- Conventional PID controllers are easy to implement and are versatile. They have fast time response but are subject to overshoot.
- Being a fixed gain algorithm, for fast response and low steady state errors they may become unstable.
- Fuzzy controllers are less susceptible to variations in the plant, external noise, and instability, permitting lower steady-state errors and faster response. They are also adaptative and rugged .

Hybrid Controller

As a means of simplifying the implementation of the algorithm, a sequential arrangement of the two types of controllers was chosen.

Each **PID** element has a specific function and acts either on its own or together for one or more response characteristics [MIRON, 1989], as follows:

- ***Proportional*** (K_p) – decrease time response and error
- ***Integral*** (K_i) – reduces the steady state error
- ***Derivative*** (K_d) – increases stability

Similarly to conventional **PID** gain, hybrid controller parameters can be adjusted, e.g., using Ziegler Nichols method. After adjusting the **PID** filter, the **PI** component is replaced by the ***Fuzzy*** system, resulting in a hybrid controller.

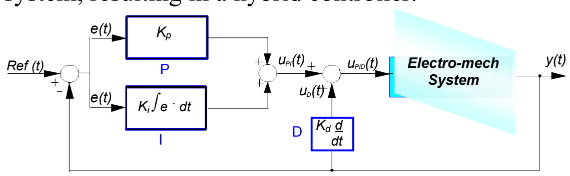

Figure 3 – Block Diagram of a conventional PID Controller.

Equations for the Hybrid Controller

Figure 3 shows the block diagram of a dynamic system controlled by a PID filter.

T – sampling time;
e(k) – input to the controller: e(k) = Ref(k) – y(k);
u(k) – output of the controller (kT).

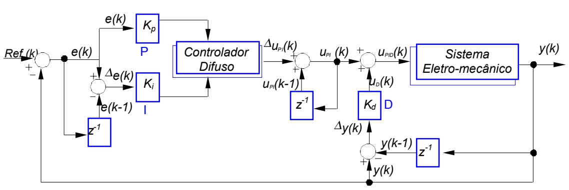

Figure 4 – Block Diagram of a Hybrid Controller "PI *difuso* + D".

In this work, the use of a hybrid "PI *fuzzy* + D" is proposed, where the integral and proportional parameters are generated by a fuzzy controller. Figure 4 shows the architecture of the system where the control signal ($u_{PID}(k)$) can be expressed as:

$$u_{pid}(k) = u_{pi}(k) - u_d(k) \quad (3)$$

generalizing,

$$u_{pid}(k) = K_{pi} \cdot \Delta u_{pi}(k) + u_{pi}(k-1) - K_d \cdot \left[\frac{\Delta y(k)}{T}\right] \quad (4)$$

$$u_{pid}(k-1) = K_{pi} \cdot \Delta u_{pi}(k-1) + u_{pi}(k-2) - K_d \cdot \left[\frac{\Delta y(k-1)}{T}\right] \quad (5)$$

which can be written in the incremental form as:

$$\Delta u_{pid}(k) = u_{pid}(k) - u_{pid}(k-1) \quad (6)$$

$$\Delta u_{pid}(k) = K_{pi} \cdot [\Delta u_{pi}(k) - \Delta u_{pi}(k-1)] + [u_{pi}(k-1) - u_{pi}(k-2)] - K_d \cdot \left[\frac{\Delta y(k) - \Delta y(k-1)}{T}\right] \quad (7)$$

In this manner, the mathematical principle, which defines the control law can be obtained as a function of the output of a PI system of the incremental type. This output can be expressed in the frequency domain as:

$$U_{pi}(s) = K_p^c \cdot E(s) + K_i^c \cdot \frac{E(s)}{s} \quad (8)$$

Where, K_p^c e K_i^c correspond to the proportional and integral gain of the controller PI and E(s), the following error signal. In the discrete form, Equation 8 becomes:

$$u_{pi}(k) = K_p \cdot e(k) + K_i \cdot T \cdot \sum_{n=0}^{k} e(n) \quad (9)$$

or,

$$\Delta u_{pi}(k) = K_p \cdot [e(k) - e(k-1)] + K_i \cdot T \cdot e(k) \quad (10)$$

$$\Delta u_{pid}(k) = \frac{u_{pi}(k) - u_{pi}(k-1)}{T} \quad (11)$$

or:

$$u_{pi}(k) = u_{pi}(k-1) + T \cdot \Delta u_{pi}(k) \quad (12)$$

As shown by MALKI et al. (1994), The term $T\Delta u_{pi}(k)$ can be replaced by a term which represents a fuzzy action of the incremental type $K_{PI}\, \Delta u_{PI\, fuzzy}(k)$, where K_{PI} is the gain of the fuzzy controller, so that:

$$u_{PI}(k) = u_{PI}(k-1) + K_{PI} \cdot \Delta u_{PIfuzzy}(k) \quad (13)$$

for K_{PI}=1:

$$\Delta u_{PIfuzzy}(k) = u_{PI}(k) + u_{PI}(k-1) \quad (14)$$

Using rules of the IF-THEN type, the fuzzy logic controller describes the relationship between the control action increment $\Delta u_{PI\, fuzzy}(k)$, the deviation of the desired value or The error e(k) at the same time and its variation "Δe(k) = e(k) - e(k-1)", thus:

$$\Delta u_{PIfuzzy}(k) = f\{e(k), \Delta e(k)\} \quad (15)$$

As can be seen, equations 10 and 15 are similar, showing that a fuzzy PI controller can replace a conventional PI. Equation 9 can be re-written as:

$$u_{PID}(k) = K_p \cdot e(k) + K_i \cdot \Delta e(k) - K_d \cdot \Delta y(k) \quad (16)$$

thus

$$\Delta u_{PIfuzzy}(k) \propto K_p \cdot e(k) + K_i \Delta e(k) \quad (17)$$

where K_p and K_i are the conventional PI controller gains. The difference is that, in the case of conventional PI the relationship is linear (constant gain) whereas in the fuzzy PI the relationship can be non-linear (variable parameters).

A Neural Network similar to the one shown in CAMPOS RUBIO et al, (1998) was used, with 5 neurons. Figure 5 shows the mapping of the fuzzy element of the hybrid controller using a neural network of two layers and 5 neurons on the intermediate layer.

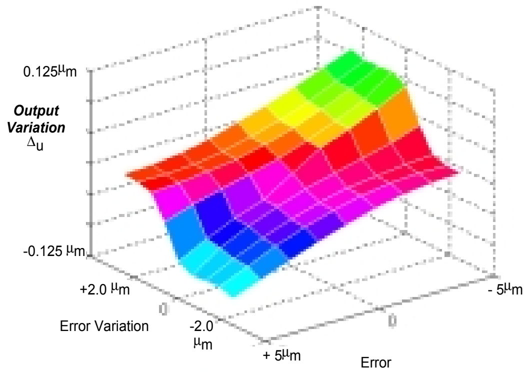

Figure 5 – Mapping of the Fuzzy Logic Controller

NUMERICAL SIMULATION AND EXPERIMENTAL TESTS

The servocontrollers were assessed in terms of time response and ability to reduce/eliminate perturbations.

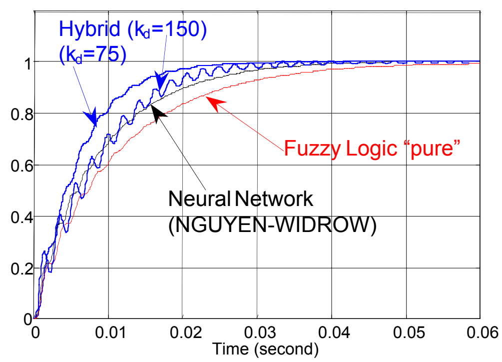

Figure 6. – Step Response.

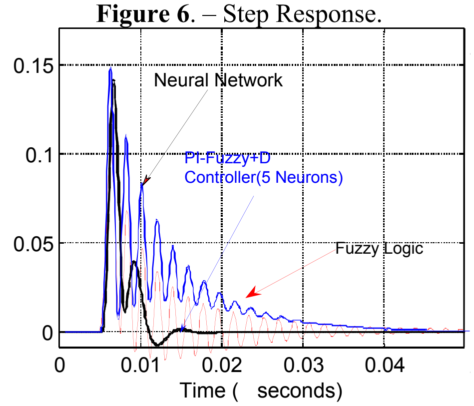

Figure 7. – Removal of Perturbation.

Figures 6 and 7 show the closed loop step and perturbation response using MATLAB® software.

The displacement amplitude using "PI *fuzzy*+D" is shown in Figure 8.

RESULTS AND DISCUSSIONS

The time response of the fuzzy neural-based controller was superior to the "pure" fuzzy. This is because of the need to interpolate values within the look-up table (linear interpolation in the case of "pure" fuzzy). PI *fuzzy* + D is an interesting option which aggregates the simplicity of the PID controller and greater control capabilities (variable

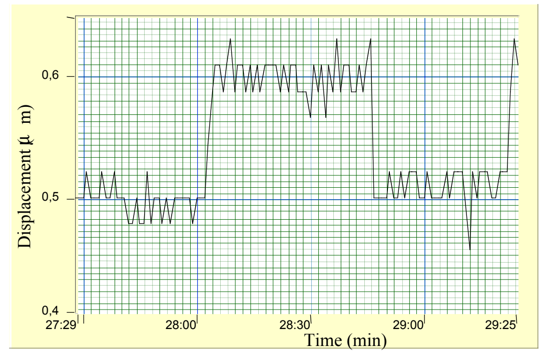

Figure 8 - PI fuzzy+D Displacement Test

in the presence of high level noise (Figure 8).

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