Adaptive Fuzzy Logic for Focusing in Optical Disk Player

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Abstract — *For the nonlinear behaviors of the actuator and servo system of the optical disk player, a fuzzy control is introduced. Focus servo controls the laser beam to focus on the playing surface of the disc by vertical movement of the objective lens. The change of the distance between the objective lens and the disc must be within the allowable focus error to stay in focus. This must be maintained even with a slightly warped or uneven disc and in a portable player. This paper will observe on how the focusing is controlled in an optical disk player and will evaluate algorithm based on the model using Adaptive Fuzzy Logic*[1].

Index Terms — Fuzzy Logic for ODP, Focusing in Optical Disk Player, Focusing using Adaptive Fuzzy Logic

I. INTRODUCTION

An optical disk has a plastic substrate that is not perfectly flat, but is slightly warped. Furthermore, when mounted in a drive, small tilts of the axis could cause vertical motions of the disk surface during operation. It is not rare to find vertical movements as much as ±100 μm during the operation of an optical disk. A typical objective lens has a numerical aperture of 0.45 or higher, and therefore, the focused beam has a depth of focus of a fraction of $\lambda/(NA)^2$, which is only a fraction of a micrometer. In optical disk player, the photodiode array provides the initial focus information along with an amplifier and a control system. A pair of coils causes the optical pick-up within the optical assembly to move vertically for the accurate and continuous focusing. When the optical pick-up is approaching to focus-error zero range (FEZR), the voice coil motor actuator response should be instantaneous. Due to the delay of response, it is possible to miss the right driving force to make the optical pick-up to be in the range. Likewise, quick response for the opposite driving force is necessary after passed the FEZR. These actions will be repeated until it reaches in the FEZR. The focused spot must remain within the depth of focus while the disk rotates at speeds of several thousand revolutions per minute and wobbles in and out of focus by as much as ±100 μm in each revolution.

The paper will describe how focusing servos are controlled, and how the Fuzzy Logic can be applied into the control with appropriate algorithm. For the first part, fuzzy logic and control will be addressed. The fuzzy logic, fuzzy set, fuzzy rule and membership function are described in terms of basic aspects. In the second part, the characteristic of the focusing in optical disk player is explained. At the end, actual focusing servo will be implemented and will be evaluated using fuzzy logic controller with appropriate algorithm.

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II. FUZZY LOGIC

The fundamental difference between fuzzy logic and traditional logic is the ability to express vagueness and uncertainty in data by means of fuzzy sets. Fuzzy sets allow representing linguistic identifiers like "tall", "medium", "about" that are closer to human reasoning. The methodology of the fuzzy logic control (FLC) appears very useful when the processes are too complex for analysis by conventional quantitative techniques or when the available sources of information are interpreted inexactly or uncertainly. Moreover, the FLC provides an algorithm, which can convert the linguistic control strategy based on expert knowledge into an automatic control strategy. Now, some of the basic concepts of fuzzy set theory and fuzzy logic, which will be helped for this paper, are summarized [1], [2].

A. Fuzzy Sets and Logic

In classical set theory, an element is either true or false of any given set – its membership value is either 1 or 0, respectively. By contrast, the fuzzy set theory is that an element can have a degree of membership between 0 and 1 in a given fuzzy set.

Fuzzy Set: A fuzzy set A in a universe of discourse U is characterized by a membership function μ_A, which takes values in the interval [0, 1] namely,

$$\mu_A : U \to [0,1].$$

A fuzzy set may be viewed as a generalization of the concept of an ordinary set whose membership function only takes two values {0,1}. Thus, a fuzzy set A in U may be represented as a set of ordered pairs of a generic element u and its grade of membership function:

$$A = \{(u,\ \mu_A(u)) \mid u \in U\}.$$

When U is continuous, set A can be written concisely as

$$A = \int_U \mu_A(u)/u\ .$$

When U is discrete, set A is represented as

$$A = \sum_{i=1}^{n} \mu_A(u_i)/u_i\ .$$

Let A and B be two fuzzy sets in U with membership functions μ_A and μ_B respectively. The set theoretic operations of subset, complement, intersection, union and implication for fuzzy sets are defined via their membership functions [3].

Subset: Given fuzzy sets A and B associated with the universe of discourse U, with membership functions denoted

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μ_A and μ_B respectively, A is defined to be subset of B, $A \subset B$, if $\mu_A \le \mu_B$ for all $u \in U$.

Complement: The membership function $\sim \mu_A$ of the complement of a fuzzy set A is defined for all $u \in U$ by $\sim \mu_A(u) = 1 - \mu_A(u)$.

Intersection: The intersection of fuzzy sets A and B, which are defined on the universe of discourse U, is a fuzzy set denoted by $A \cap B$, with a membership function defined by either of the following two methods:

1. Minimum: $\mu_{A\cap B}(u) = \min\{\mu_A(u), \mu_B(u) : u \in U\}$
2. Algebraic Product: $\mu_{A\cap B}(u) = \{\mu_A(u) \cdot \mu_B(u) : u \in U\}$

Union: The union of fuzzy sets A and B, which are defined on the universe of discourse U, is a fuzzy set denoted by $A \cup B$, with a membership function defined by either one of the following methods:

1. Maximum: $\mu_{A\cup B}(u) = \max\{\mu_A(u), \mu_B(u) : u \in U\}$
2. Algebraic Sum:
$$\mu_{A\cup B}(u) = \{\mu_A(u) + \mu_B(u) - \mu_A(u) \cdot \mu_B(u) : u \in U\}$$

Implication: The implication of fuzzy sets A and B, which are defined on the universe of discourse U, is a fuzzy set denoted by $A \Rightarrow B$, with a membership function defined by $\mu_{A\Rightarrow B}(u) = \min\{1, 1 - \mu_A(u) + \mu_B(u) : u \in U\}$.

B. Membership Function

A functional definition expresses the membership function of a fuzzy set in a functional form, typically a bell-shaped function, triangle-shaped function and trapezoid-shaped function. The functional definition can readily be adapted to a change in the normalization of a universe. This paper will only consider the general situation with triangular membership function, and the mathematical characterization of the membership function can be defined as [4]

Left:

$$\mu_L(x) = 1, \text{ if } x \le C_L$$
$$\mu_L(x) = \max\{0, 1 + \frac{C_L - x}{0.5\omega_L}\}, \text{ Otherwise}$$

Centers:

$$\mu_C(x) = \max\{0, 1 + \frac{x - C}{0.5\omega}\}, \text{ if } x \le C$$
$$\mu_C(x) = \max\{0, 1 + \frac{C - x}{0.5\omega}\}, \text{ Otherwise}$$

Right:

$$\mu_R(x) = \max\{0, 1 + \frac{x - C_R}{0.5\omega_R}\}, \text{ if } x \le C_R$$
$$\mu_R(x) = 1, \text{ Otherwise}$$

where C_L and C_R = saturation points,
ω_L and ω_R = slopes of the nonunities and nonzero parts of μ_L and μ_R,
C = center of the triangle, ω = the base-width

Typically, there are six types of the membership functions, such as symmetric inclusive, symmetric exclusive, right inclusive, right exclusive, left inclusive and left exclusive. In addition, terms are listed as Zero (ZE), Nearly Negative (NN), Nearly Positive (NP), Small Negative (SN), Small Positive (SP), Medium Negative (MN), Medium Positive (MP), Large Negative (LN) and Large Positive (LP).

C. Fuzzy Rule

The dynamic behavior of a fuzzy system is characterized by a set of linguistic description rules based on expert knowledge. The expert knowledge is usually of the form IF (a set of conditions are satisfied) THEN (a set of consequences can be inferred). A fuzzy control rule is a fuzzy conditional statement in which the antecedent is a condition in its application domain and the consequent is a control action for the system under control. In other words, the consequences from all fired rules are computed. Then the outputs are numerically aggregated by the fuzzy OR operator and finally defuzzified to yield a single real number output. The fuzzy rule consists of a set of arguments $A_{i,k}$ in the form of fuzzy set with membership functions $\mu_{A_{i,k}}$ and a consequence C_i in the form of a fuzzy set [5]. Each method of composition of fuzzy relations reflects a special inference machine and has its own significance. It is claimed that Max-Min method of composition of fuzzy relations correctly reflects the approximate and interpolative reasoning used by human when using natural language propositions for deductive reasoning [6]. Hence, the Max-Min Composition follows

$$y^k = x \bullet R^k$$
$$\mu_{y^k}(y) = \underset{x\in X}{Max}\ \{Min\ [\mu_X(x),\ \mu_{R^k}(x,y)]\} \quad (1)$$

where R^k is fuzzy relation, and y^k, for k = 1,2,…,r, is the output of the system contributed by the k[th] rule.

For a system of disjunctive fuzzy relations, the aggregated output y is found based on the definition of Union and the composition (1) as following (Max-Min Method):

$$\mu_y(y) = \underset{k}{Max}\ \{\underset{x\in X}{Max}\ \{Min\ [\mu_X(x),\ \mu_{R^k}(x,y)]\}\}$$

where $\mu_y(y)$ is the fuzzy membership function describing the overall output response to the fuzzy input x.

For the case of a system with n non-interactive fuzzy inputs, the aggregated output will be in the following form:

$$\mu_y(y) = \underset{k}{Max}\{\underset{x\in X}{Max}\{Min\ [\mu_{X_1}(x_1),\ \mu_{X_2}(x_2),\ \cdots,$$
$$\mu_{X_n}(x_n),\ \mu_{R^n}(x_1, x_2, \cdots, x_n, y)]\}\}$$

where $x = [x_1, x_1, \cdots, x_n]$ is the vector of n non-interactive inputs to the fuzzy system.

D. Fuzzy Components

Fuzzy control provides a formal methodology for representing, manipulating, and implementing a human's heuristic knowledge about how to control a system. The fuzzy controller has four main components: fuzzification interface, fuzzy control rule base and membership function, decision-making logic, and defuzzification interface. Each component is described as following:

- *The fuzzification interface*: Functions are measuring the values of input variables, performing a scale mapping that transfers the range of values of input variables into corresponding universes of discourse, and performing the function of fuzzification that converts input data into suitable linguistic values, which may be viewed as labels of fuzzy sets.
- *The fuzzy control rule base and membership function*: It comprises knowledge of the application domain and the attendant control goals. The membership function provides necessary definitions, which are used to define linguistic control rules and fuzzy data manipulation in an FLC, The fuzzy rule base characterizes the control goals and control policy of the domain experts by means of a set of linguistic control rules.
- *The decision-making logic*: It is the kernel of an FLC and has the capability of simulating human decision-making based on fuzzy concepts and of inferring fuzzy control actions employing fuzzy implication and the rules of inference in fuzzy logic.
- *The defuzzification interface*: It performs a scale mapping, which converts the range of values of output variables into corresponding universes of discourse and defuzzification, which yields a non-fuzzy control action from an inferred fuzzy control action.

III. FOCUSING IN OPTICAL DISK PLAYER

The head amplifier incorporates transresistance amplifiers that convert the six current signals from the optical pick-up to voltage signals. It derives three vital analog signals, such as the RF signal, the focus error signal and the tracking error signal. The focus error signal is fed to the digital signal processor (DSP) chip. A feedback circuit is incorporated to receive signal from the monitor diode, and subsequently to regulate the current to the laser diode. The DSP chip performs a servo control function. The digital servo circuits inside this chip receive the focus error (FE) signals from the head amplifier and control the currents to the focus coil, hence maintaining the optical lens in focus.

The light emitted by the laser diode is converted into circularly polarized light and then focused down onto the disk. When the vertically polarized light hits the polarizing beam splitter, it will be reflected. The reflected beam strength is transferred to Photo-Detect Diode by Beam Splitter as shown in the Fig. 1.

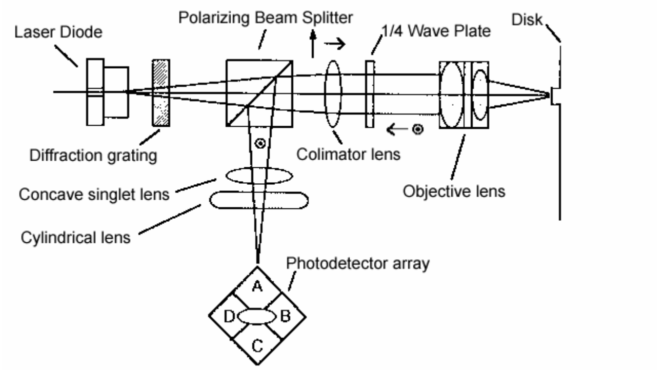

Fig. 1. Optical Assembly

The objective lens is mounted in a voice coil actuator, and a feedback mechanism is used to drive the lens towards and away from the disk in such a way as to maintain focus at all times. The signal needed for this feedback mechanism is derived from the light that is reflected from the disk itself. The light reflected from the disk and collected by the objective lens is either convergent or divergent, depending on whether the disk is further away from best focus or closer to the lens than the plane of best focus. The returned beam goes through a cylindrical lens, which normally focuses the incident beam to a symmetric spot halfway between its focal planes. A quad detector placed at this plane and then receives equal amounts of light on its four quadrants. If the objective lens is closer to or further away from the disk than the focal length of the object lens, the cylindrical lens creates an elliptical image on the photodetector array. However, if the disk is right at the focal length of the objective lens, then it will be perfectly circular image [7].

Using optical feedback from the disk surface, the focusing is accomplished with a coil type of positioner by moving up and down. In other words, depending on the sign of defocus, this elongated spot may preferentially illuminate quadrants A and C or quadrants B and D of the detector. Therefore, the combination signal (S_A+S_C) - (S_B+S_D) provides a bipolar focus-error signal, which is fed back to the voice coil for maintaining focus. This must be maintained even with a slightly warped or uneven disk and in a portable player.

IV. FOCUSING USING ADAPTIVE FUZZY LOGIC CONTROLLER

The implementation in fuzzy logic uses fuzzy variables and fuzzy rules from analyzed behavior rather than mathematical modeling. The simulation was conducted using the one of the stand-alone fuzzy controller characteristics from Adaptive Logic that supports 40 MHz system clock cycle, four 8-bit analog I/O ports and six types of membership functions. The four inputs are executed through the pipeline process. Each input value takes 1024 clocks to execute and to produce the corresponding output, and the I/O timing is illustrated in the Fig. 2.

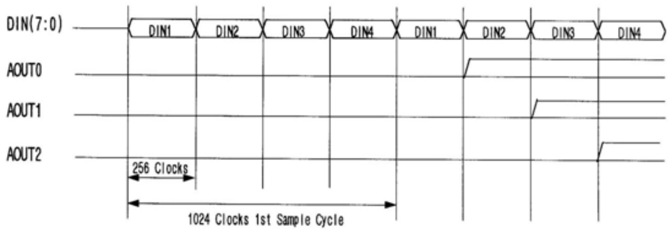

Fig. 2. I/O Timing

Two methods are available for the defuzzification, one for immediate method, which drives an output with a specific value, and the other one for accumulate method, which adds the previous output value to the newly calculated value. This paper used the accumulate method for the fuzzy rule. For the simulation, CD-ROM was used to verify the focusing using the fuzzy controller. In addition, some of the evaluation was dealt during the implementation. For more detailed information on how the servo and the fuzzy application work can be found in [8]–[15].

A. Consideration

For the optical disk player, the smallest optical spot size that can be achieved is determined by the diffraction limit, which is proportional to λ/NA where λ is the optical wavelength and NA is the numerical aperture. The areal density is proportional to the inverse square of this quantity. As NA is increased or λ is reduced, the system tolerances become much more severe [16].

The surface vibration height and the vibration acceleration should be within ±500 μm and 10 m/s^2 respectably when the frequency is below 500 Hz. On the other hand, the maximum height should be ±1 μm when the frequency is above 500 Hz. With the consideration of beam's scatter, the displacement for the focusing should be sustained within ±1.0 μm. With 40 MHz system clock cycle, it takes about 25.6 μs for the fuzzy controller to output the calculated value from the input. In other words, the response of surface vibration change should be scalable to the change of the focus error in 25.6 μs to satisfy the focus servo. Hence, the change response for the surface vibration should be calculated and executed within 25.6 μs.

B. Implementation in Fuzzy Controller

The photodetector diode sends the FE value to analog-to-digital converter in the fuzzy controller for the fuzzification. Then the fuzzy controller outputs an adjusted value (Fadj) by running the rule based fuzzy program for optical pick-up drive to come to the best position of the lens. In Focus Searching mode, the lens moves along the consistent path, and then the focus servo is changed to FZC mode when the lens approaches to the focus zero crossing (FZC) area. The algorithm will let the lens movement to be slow when it approaches to FZC area and to be fast when it is far from the FZC area using the fuzzy logic rules. For the Fadj control algorithm to make FE to be "0" level using the fuzzy controller will follow the function of $(FE)^3$ as indicated on (2).

$$F_{adj} = a \cdot (FE)^3 \quad \text{where } a \text{ is FE change response rate} \tag{2}$$

Two input signals, Fmode and FE, are used for the focus servo control. The Fmode sets either FZC mode or Focus Searching mode to apply corresponding fuzzy rules. FE input signal is produced by photodetector and fuzzified for the membership function. The accumulated Fadj value after the defuzzification is produced for the Focus Driver as shown on Fig. 3.

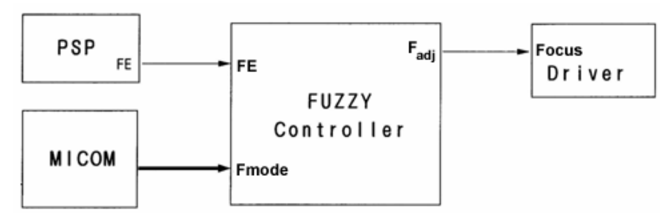

Fig. 3. Focus Fuzzy Servo Physical Diagram. The controller is in FZC mode when Fmode = 1 and Focus Searching mode when Fmode = 0.

The change of the distance between the objective lens and the disk must be within the allowable focus error to stay in focus as shown in Table 1 [17].

TABLE I
SPECIFICATIONS OF THE OBJECTIVE LENS

PARAMETER	CD	DVD	BLU-RAY
OPTICAL WAVELENGTH (λ) (nm)	780	658	405
NUMERICAL APERTURE (NA)	0.45	0.65	0.85
FOCAL DEPTH ($\lambda/(NA)^2$) (μm)	±1.9	±0.8	±0.28
ALLOWABLE FOCUS ERROR (μm)	±1.0	±0.11	±0.046

With 8-bit resolution, 256 different values of FE and Fadj can be inputted and outputted respectably for the focusing fuzzy controller. Hence, the corresponding resolution of the analog input for FE can be scaled to 0.023 μm/b to cover up to the Blu-ray, which can be swung within ±2.944 μm. This gives just enough room for the focus depth with the allowable focus error. On the other hand, if we give a bigger corresponding resolution for FE, such as 0.055 μm/b, to cover up to the DVD, it can be swung within ±7.04 μm and will cause the optical disk player to reach FEZR faster. The membership function for the fuzzy input FE is illustrated in Fig. 4.

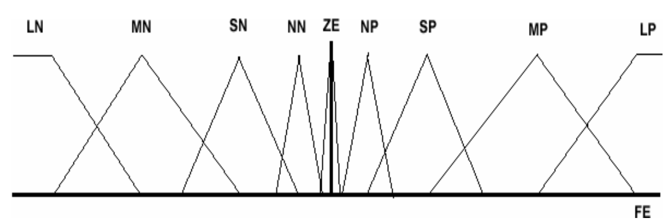

Fig. 4. Fuzzy input FE membership function

As explained previously, the membership function is tightly joined near the ZE area because the Zero Crossing might be occurred where the focus error value is changed rapidly. The assignment of input variable FE for the membership function is shown on the Table 2.

TABLE 2
MEMBERSHIP FUNCTION FOR FOCUSING

FE	CENTER	WIDTH	TYPE
ZE	128	2	SYMMETRIC INCLUSIVE
NP	133	8	SYMMETRIC INCLUSIVE
NN	123	8	SYMMETRIC INCLUSIVE
SP	147	27	SYMMETRIC INCLUSIVE
SN	109	27	SYMMETRIC INCLUSIVE
MP	179	64	SYMMETRIC INCLUSIVE
MN	77	64	SYMMETRIC INCLUSIVE
LP	211	63	LEFT INCLUSIVE
LN	45	63	RIGHT INCLUSIVE

The fuzzy rules for the Fadj are divided for FZC mode and Search mode using accumulate method, and the rules are assigned on the Table 3.

TABLE 3
FUZZY RULE FOR FOCUSING

Fadj		Fmode	
		Search	**FZC**
FE	**LN**	-63	-32
	MN	-32	-16
	SN	-14	-7
	NN	-4	-1
	ZE	1	0
	NP	4	1
	SP	14	7
	MP	32	16
	LP	63	32

By applying the membership function and the fuzzy rule to the fuzzy controller, the simulation results came up as illustrated in Fig. 4.

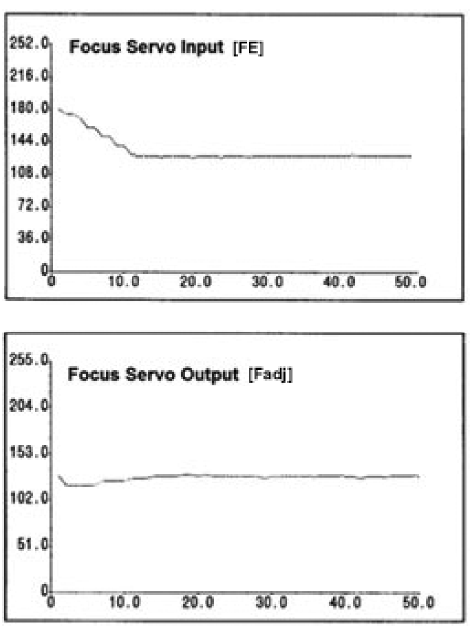

Fig. 4. Simulation results from Focus Fuzzy Servo

The simulation shows that the focusing has established after about 12 iterations and indicates that the implementation using the fuzzy logic controller has succeeded for the optical disk player.

V. CONCLUSION

The experiment shows that the fuzzy logic based controller took less iteration than conventional focusing servo, which took about 32 iterations. In other words, the fuzzy logic controller has better response for non-linear system than conventional logic controller does. However, the experiment did not consider random shocks from the external source. This may require additional mode for the random shock with a compensation voltage provider as an offset voltage at the focus driver, the fuzzy controller with higher resolution than 8-bit, and with faster execution cycle.

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