Improved Auto-Focus Search Algorithms for CMOS Image-Sensing Module*

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Digital image capturing devices currently available in the market include camera phone, webcam, and vehicle rear-view camera. With the advancement in lens module manufacturing technologies, efforts have been made to improve the image quality, diversify the product functions, and reduce the product size. Facing the large market demands, it is important to achieve higher lens module output in mass production. Under this trend, the process of focusing the large quantity of lenses efficiently is an issue to be concerned. The conventional active auto-focusing (AF) technology relies on distance measuring equipment to measure and adjust the relative distance between the object and the lens. Whereas, passive AF technology does not require any distance measuring equipment; instead, it employs digital images acquired by the lens to calculate the sharpness of the image, which serves the basis for changing the lens focus, and searching for the imaging position with a focus value that has reached the threshold. The most important condition for AF algorithm is the real-time feature; however, it is time-consuming for regular search algorithms to solve the focusing problem. To solve this issue, this research proposes to integrate the intelligent fuzzy control theory and the fuzzy sliding-mode controller, which is characterized by its sliding surface, to build an AF system controller. The controller can control the rotary angle of the motor that drives the lens movement, in order to achieve CMOS image-sensing module AF quickly.

Keywords: CMOS, auto-focus, fuzzy control theory, sliding surface, fuzzy sliding-mode controller

1. INTRODUCTION

With the advancement in electro-optical technologies in recent years, the application and development of various image-sensing technologies have become increasingly extensive. Electronic imaging products, such as camera phone, webcam, vehicle rear-view camera, and laparoscope, have been introduced with improving quality. These image-sensing devices can be divided into two types: charge coupled device (CCD) and complementary metal-oxide semiconductor (CMOS). In the past, CMOS sensor was inferior to CCD in terms of image quality. However, CMOS sensor made breakthroughs in core technologies, such as analog circuit design, photoelectric diode manufacturing structure conversion and image digitalization, thus, has successfully solved problems of noise and light sensitivity. In addition to the support from semiconductor manufacturing technology and packaging technology, CMOS image sensor has advantages of energy-saving, compact size, low cost, and easy integration, thereby is considered having significant development potentials [1, 2]. At present, the focusing of image sensor modules is carried out manually

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by visual inspection. Thus, the image quality may be affected by human errors or subjective determination, as human eyes are prone to misjudgement near the focusing point. As a result, a fast and automatic focusing technique needs to be developed.

Considering the above problems of auto-focus in machine vision system, this paper presents a novel auto-focus algorithm combining the fuzzy controller and sliding surface. The proposed scheme can predict the developing trend of the focus value curve to identify the best-focused lens position by few sampling focus values, thus reducing the computational load of the measuring focus value and enhancing the reliability of the auto-focus process.

The remainder of this paper is organized as follows. Section 2 discusses the currently used focus value algorithm and search algorithm for auto-focus. Section 3 describes the principle of image formation and modulation transfer function (MTF). Section 4 presents the calculation of focus search algorithm proposed by this paper. Section 5 compares the experimental results of the proposed focus search algorithm and the current method. Finally, the concluding remarks are given in the last section.

2. RELATED WORK

The conventional active auto-focusing (AF) technology relies on distance measuring equipment to measure and adjust the relative distance between the object and the lens. Whereas, the passive AF technology does not require any distance measuring equipment; instead, it acquires digital image by the lens to calculate the focus value of the image. Then, by using the focus searching algorithm, the lens focus can changed to find the imaging position that has reached the threshold, in order to present the sharpest image [3, 4]. The research can be divided into two parts: focus value algorithm, and the search algorithm for AF.

In sharp images, edges can be seen, and the gray scales of adjacent pixels vary significantly, especially on the edges. The obscure image has no such features. Therefore, this feature can be used as an indicator for image sharpness, which is called the definition value. The image definition calculation includes frequency transforming or spatial domain calculation, thus definition value is set as an indicator for judging the sharpness of the image. Nayar et al. [5] applied the fast Fourier transform (FFT) to calculate the image and analyze the transform result. Higher Fourier spectrum indicates that the capture image has good sharpness. Widjaja et al. [6] used the Wavelet transform method to highlight the characteristics of the image edge so as to obtain higher resolution. Zheng et al. [7] applied the marginal position of the captured target to calculate the contrast and variations on both sides of the margin. Higher contrast variation indicates that the image has good sharpness. He et al. [8] applied the focus value is generally based on illuminant gradient of an image. It often refers to the sum of the absolute gradient or the gradient energy of pixels in an image.

The passive AF system not only requires the definition algorithm, but also a set of efficient search algorithm for finding the focus, in order to achieve fast AF. The auto-searching algorithm is to use the distance between the lens movements to measure the definition values of the two positions as reference distance. The search actions are repeated to approach the focus slowly. If the search algorithm misses the position close to the peak value, it is not easy to find the focusing point within the threshold values. Chern et al. [9]
proposed a global search algorithm, which records the position value of each point within the lens working distance and calculates the definition value of that point, in order to obtain the global maximum sharpness and present the best image. However, the global search method is a time-consuming search algorithm due to its high computational load, which increases with the number of image pixels. Binary and rule-based search algorithms are two other methods used to perform the auto-focus process for machine vision [10, 11]. Fig. 1 shows the three implemented search algorithms. It can be seen that the ruled-based search is the best auto-searching algorithm for these three search algorithms [3].

According to past studies, the image sharpness can be obtained by frequency transform and spatial domain methods. The computation of the frequency transform is rather complicated, thus reducing the computational efficiency. Thus, the spatial domain computation is the main tool to calculate the image sharpness [12], of which, modulation transfer function (MTF) is more convenient and accurate. Therefore, this research adopted MTF as the computation rule of the image sharpness.

However, the current AF methods are time-consuming, require long moving distance due to overshooting, and capture images with still lens in order to prevent image noise. As a result, the AF method still has room for improvement.

This paper applied fuzzy sliding theory to develop an auto-focus control system, which enables the lens to search for the optimal focus so as to capture the sharpest images, and ensures the system to have better execution efficiency. Since it is time-consuming to apply the fuzzy controller on the membership functions and control rule design, this paper used sliding plane surface to replace the two fuzzy input variables in order to greatly decrease the complexity of the system and obtain the optimal parameters combination of membership functions and control rule. As a result, AF efficiency can be enhanced, and sharp images can be captured.

3. FOCUS VALUE ALGORITHM

This section first introduces the imaging principle, and then describes the principles and equations of the focus value algorithm for MTF.
3.1 Image Acquisition

In machine vision, one of the important factors that influence the measuring performance is the manner in which clear images are obtained stably and continuously. That is, if the acquired image is blurred, it is possible that a large amount of information pertaining to the edge data that is to be measured will be lost; as a result, stable results cannot be obtained.

Basically, the theorem of object captured by image capturing devices and the formation of image are shown in Fig. 2 [12]. All parallel rays are focused to a point which is referred to as the principal focal point, i.e., the position of image sensor. The distance from lens to this point is given by the principal focal length \( f \) which is set by the lens manufacturer according to the parameters of lens. Let the distance between lens and a captured object be \( o \), the distance between lens and the principle focal point be \( i \), then the relationship among distances \( f, o, \) and \( i \) can be expressed by Eq. (1).

\[
\frac{1}{f} = \frac{1}{o} + \frac{1}{i}
\]  

(1)

![Fig. 2. Formation of focused images.](image)

3.2 Modulation Transfer Function (MTF)

Image can be divided into various spatial frequencies; the imaging quality reflects the transfer and response capacity of the imaging system to respective spatial frequency, and is expressed in data. In the MTF, the contrast concept is used to examine the quality of the imaging system, and is normally measured by the sinusoidal grating chart of various spatial frequencies (linepairs/mm) [13], as shown in Fig. 3.

![Fig. 3. Sinusoidal grating chart.](image)

![Fig. 4. Relationship between spatial frequency and image contrast.](image)
Given a fixed length and smaller spatial frequency, it is easier to identify the lines and obtain sufficient contrast ratio from the image. As the spatial frequency increases, the lines become denser, and the contrast ratio reduces. When the image attenuates to total gray, as it is impossible to differentiate the black and white stripes, it means that the resolution of the lens has reached its limit. Fig. 4 shows the relationship between the spatial frequency and the image contrast.

This concept can also be applied on focusing. The variable of the original spatial frequency is replaced by the measured distance, thus, the MTF of black and white contrast can be defined as follows,

$$MTF = \frac{H - L}{H + L} = \frac{H - L}{2},$$

where $H$ is the mean value of gray scale, from the gray scale mean value to 225; $L$ is the mean value from 0 to the gray scale mean value.

4. AUTO-FOCUS SEARCHING ALGORITHM

This section describes the fuzzy control and the fuzzy sliding control, as well as the design of controller.

4.1 Fuzzy Controller Structure

To design a auto-focus controller in traditional control system, the controlled system had to be characterized with a mathematic model. And all variables of system must be thoroughly understood before completing design. As to huge, nonlinear or hard-to-measure controlled system, the more variables to consider, the more complex the problem to deal with. Nonetheless, to design controller by using fuzzy control theory can simplify complexity of system design, especially for nonlinear, time dependant and incompletely modeled systems [14-16]. Furthermore, fuzzy controller was a kind of nonlinear control tool easy to master, thus had better adaptation, robustness and fault tolerance.

Fuzzy theory has a history of 32 years since Zadeh [17] published Fuzzy Sets, fuzzy theory has many application cases in various trades, fuzzy control is one of most honored applications of fuzzy theory, which implants human decision model into process of controller design, so that design of a control system is not dependent on mathematic model inference. This paper will also utilize fuzzy control theory to design auto-focus control, and investigate its control performance.

Basic structure of fuzzy control system mainly included five parts, as shown in Fig. 5. Input variable, fuzzifier, control rule, process logic, defuzzifier. Where

**Input variable**: in terms of input variable of common control system, system output error $e$ and error variation $\dot{e}$ can be determined; control variable in controller output rule is $u$, these three variables, $e$, $\dot{e}$ and $u$ are fuzzy variables.
Fuzzifier: transform definite input variables to fuzzy domain.

Control rule: control rule is the core of fuzzy controller, and the basis for judging output, basically fuzzy controller is a rule-decision system, the rule is demanded by system or made based on human experience, normally the fuzzy conditional phrase representing control rule is abbreviated to a table format, called fuzzy decision control table, as fuzzy control consists of control rule in language pattern, hence it’s easy to understand controller action through control rule, and incorporate specially enhanced control rule corresponding to response of part of system, thus improving system control, or adding human experience while modifying rule, to attain the purpose of control. Therefore nonlinear fuzzy control of controlled system unable to be described accurately in linear mathematic model, after properly adjusting rule, shall have better control performance than traditional control method.

Process logic: this part is the heart of fuzzy controller, through which the needed fuzzy control signal is obtained by fuzzy judgment.

Defuzzifier: fuzzy controller input has to be fuzzified, in order to convert definite value into a fuzzy set, fuzzy controller output is a fuzzy set, too, defuzzifier is to transform this fuzzy set to a definite term, and deliver to controlled system, there are many defuzzifier methods, more common ones are shown below:

1. Center of gravity: Means the center of gravity for obtaining the shadow area of the inference result for which, the corresponding element will be used as the output. The distributed center of gravity can reduce the calculation quantity for reducing the calculation time.

\[
Y^* = \frac{\sum_{i=1}^{n} \mu_i Y_i}{\sum_{i=1}^{n} \mu_i}.
\]
where $\mu_i$ is the suitable degree of the $i$th control rule of the antecedent, $Y_i$ is the center point corresponding value of membership function for the consequence of the $i$th control rule.

2. Mean of maximum: The crisp value will be obtained by averaging the points that enable membership function reaches the maximum value. Presuming a total of $N$ points can be set to enable membership function to reach the maximum value, then:

$$Y^* = \frac{1}{N} \sum_{i=1}^{N} Y_i,$$  \hspace{1cm} (4)

where $Y_i$ represents the center point corresponding value of membership function for the consequence of the $i$th control rule.

3. Modified mean of maximum: After arranging the sequential order of aforesaid $N$ points add the maximum and minimum values together and then divide by 2 and the result is the final crisp value as below:

$$Y^* = \frac{\max(Y_i) + \min(Y_i)}{2},$$  \hspace{1cm} (5)

where $Y_i$ represents the center point corresponding value of membership function for the consequence of the $i$th control rule.

4. Midpoint of maximum: The center of area defuzzifier is more complicated and time wasting, as the area and the center of gravity must be calculated separately so as to finalize the crisp value.

$$Y^* = \frac{\sum_{i=1}^{n} A_i W_i}{\sum_{i=1}^{n} A_i},$$  \hspace{1cm} (6)

where $A_i$ represents the area enclosed by the inference result of the $i$th control rule and $W_i$ represents the center of gravity for such part.

In this paper, fuzzy controller for auto-focus searching algorithm uses MTF and MTF variation (dMTF) as the controller input and the lens position as the output. Next, they were multiplied by a coefficient $G$ to adjust size. Fig. 6 shows a block diagram of the fuzzy controller. Membership functions are normally classified as bell, triangle, trapezoid types, triangle type was adopted in this paper, because triangle operates easier, with effect not much different from other two types. The membership function chart is shown in Fig. 7. This fuzzy system, which has two inputs and one output, contains a total of 15 control rules. The fuzzy control rule is shown in Table 1, where NB denotes negative big, NS denotes negative small, ZR denotes approximately zero, PS denotes positive small, and PB denotes positive big. Finally, this paper used center of gravity to defuzzify.
4.2 Fuzzy Sliding-Mode Control

Fuzzy sliding-mode control is combined with fuzzy control and sliding surface. A common problem in realizing the fuzzy controller is the long time spent on designing the membership functions of the two-dimensional space and the rule base. Therefore, the one-dimensional sliding plane surface is used to replace the original two-dimensional control rule base in this paper, which could greatly reduce the complexity of the membership functions and control rule, and obtain the optimal parameters combination of the membership functions and control rule.

Three sufficient and necessary conditions of sliding-mode are as shown in Fig. 8 and described as follows [18],

1. Approaching condition: no matter what the state trajectory of the system, \( x(0) \), begins, at finite time interval, the state will approach to the sliding surface, \( s(x) = 0 \).
2. Sliding condition: when the state trajectory reaches to sliding surface, the state will slide in the plan and approach to the equilibrium point.
3. Stable: the final state will arrive at stable point, \( x(\infty) = 0 \). This is so called the equilibrium point.

According to the above features, the system status can eventually converge to stability by keeping the system moving on the sliding surface. The proof is as the follows.
The mathematical model of the general nonlinear systems

\[ x^{(n)} = f(X) + u, \]  

where \( X = [x \ x' \cdots x^{(n-1)}]^T \) is the system state vector, \( f(X) \) is the nonlinear state function of the system, and \( u \) is the control input signal of the system.

If

\[ f(X) = f_m + \Delta f, \]  

\[ |\Delta f| \leq \lambda(X, t) > 0, \]  

where \( f_m \) is the estimated value of the system, \( \Delta f \) is the unknown variance of \( f(X) \), and \( \lambda(X, t) \) is the function with boundary.

According to Eqs. (7) and (8) that:

\[ x^{(n)} = f_m + \Delta f + u. \]  

A system can be design so that when \( t \to \infty \), the system output value \( x(t) \) of can approach \( x_d(t) \), as shown below:

\[ \lim_{t \to \infty} [x_d(t) - x(t)] = 0, \]  

\[ e(t) = x_d - x. \]  

The following equation can be acquired by differentiating the error \( e(t) \):

\[ \dot{e}(t) = \dot{x_d} - \dot{x}, \]  

\[ \vdots \]  

\[ e^{(n)}(t) = x_d^{(n)} - x^{(n)} = x_d^{(n)} - f_m - \Delta f - u. \]  

The equation of defining the sliding plane surface is as follows,
\[ \sigma(t) = 0 \]  

where

\[ \sigma(t) = \left( \frac{d}{dt} + \alpha \right)^{n-1} e(t), \alpha > 0, \]  

and

\[ \dot{\sigma}(t) = \left( \frac{d}{dt} + \alpha \right)^{n-1} \dot{e}(t), \]  

when \( n = 2 \)

\[ \sigma(t) = \left( \frac{d}{dt} + \alpha \right) e(t) = \dot{e}(t) + \alpha e. \]  

According to Eq. (12) that:

\[ e(t) = r - y, \]
\[ \dot{e}(t) = -\dot{y}, \]

where \( r \) is the objective value, \( y \) is the system actual output.

According to Eqs. (18) to (20) that:

\[ \sigma(t) = -\dot{y} + \alpha(r - y) = 0. \]  

By using Laplace transform with input,

\[ \alpha \left[ \frac{\mathcal{L}}{s} - Y(s) \right] - sY(s) = 0, \]  

\[ \frac{\mathcal{L}}{s} \equiv (\alpha + s)Y(s), \]  

\[ \frac{Y(s)}{r} = \frac{1}{s} + \frac{-1}{s + \alpha}. \]  

From inverse Laplace transform

\[ y(t) = y - re^{-\alpha t}, \]
\[ \lim_{t \to \infty} y(t) \approx r. \]  

That proved the final status of the real output of the system will approach the desired target values.

In this paper, fuzzy sliding-mode controller for auto-focus searching algorithm of machine vision system was shown in Fig. 9. The fuzzy sliding-mode controller includes two major parts: sliding surface and general fuzzy controller. The fuzzy sliding-mode controller in this research first integrates the fuzzy controller input variables of MTF and dMTF into a new variable, sliding surface \( \sigma \).
This paper want the system get 95% of the objective value at finite time 1 sec. Then

\[
\frac{y}{r} = 1 - e^{-\alpha t} = 1 - e^{-\alpha} > 0.95.
\]  

(27)

By choosing \( \alpha = 3 \), then

\[
\frac{y}{r} = 1 - e^{-3} = 0.9502 > 0.95,
\]  

(28)

where \( \alpha \) is the slope of the sliding surface.

Then, input variable \( \sigma \) and output variable \( u \) used five fuzzy sets to divide fuzzy membership functions, NB, NS, ZR, PS and PB, respectively. Since FV curve is a nonlinear relation of parabolic curve, the membership functions are not suitable for equal quantity partition. When the auto-focus searching approaches the optimal focal point, overshoot may easily occur. By extending the triangular peak of the defining range of the input language items outwardly, the stability degree of the search focal point convergence. As a result, the triangular peak then converges inwardly to overcome some nonlinear phenomena. The output rotation angle of the motor is large when the optimal focal point is deviated during the auto-focus searching process. The rotation angle is small when the optimal focal point is approached the optimal focal point, so as to avoid overshoot. As shown in Fig. 10. Auto-focus control system of machine vision with 5-rules fuzzy sliding-mode controller, was shown in Table 2.

![Fig. 9. Fuzzy sliding-mode controller block diagram.](image)

![Fig. 10. The membership function of fuzzy sliding-mode controller.](image)

**Table 2. The control rule of fuzzy sliding-mode controller.**

<table>
<thead>
<tr>
<th>( \sigma )</th>
<th>NB</th>
<th>NS</th>
<th>ZR</th>
<th>PS</th>
<th>PB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Out</td>
<td>NB</td>
<td>NS</td>
<td>ZR</td>
<td>PS</td>
<td>PB</td>
</tr>
</tbody>
</table>
5. PERFORMANACE EVALUATION

In order to validate the proposed auto-focus searching algorithm, this paper used the sinusoidal grating chart with gray scale changing according to sinusoidal period, the license plate images with gray scale distributed in higher and lower region, and the randomly captured images with gray scale distributed in the regions evenly as the experimental samples. Fuzzy and fuzzy sliding-mode search results were compared with the currently existing best global search algorithm-rule-based search result. The following subsections describe the experimental equipment and results.

5.1 The Experimental Equipment

In these experiments, the proposed auto-focus searching algorithm was implemented on a machine vision system, as shown in Fig. 11. The machine vision system was operated and controlled by control software coded using Borland Delphi, and the control software communicated with the machine vision system through USB interface on a general personal computer.

The main components of auto-focus control module include a CMOS image sensing module, a positioning pneumatic cylinder, and a stepping motor. The CMOS image sensing module is driven by using the pneumatic cylinder so as to combine the gear on the top of the lens and the focusing stepping motor. After positioning and capturing the image, the images are converted to digital signal and transmitted to the computer for computation of the sharpness. The calculated sharpness is then used as the reference for focusing point.

![Fig. 11. AF control module diagram.](image)

![Fig. 12. Flow chart of AF control action.](image)
search, in order to drive and control the motor movement. When the motor reaches the designated position, the system captures the image gain to compute the sharpness. The above steps are repeated until the optimal focusing points are found. AF control action flow chart was shown in Fig. 12.

5.2 The On-Line Experimental Results

The sinusoidal grating chart (sample 1), the license plate image (sample 2), and the randomly captured image (sample 3) were selected as the experimental samples. Figs. 13-15 show the curve diagrams of focus values before and after normalization. The validation method is as follows,

1. Select 10 different focus positions as the starting points of focusing.
2. Use the rule-based search in the global search algorithm and the proposed method for AF.
3. Conduct statistical comparison.

Fig. 13. The sinusoidal grating chart and focus value curve chart (where the best-focused lens position is 51).

Fig. 14. The license plate image and focus value curve chart (where the best-focused lens position is 48).

Fig. 15. The randomly captured image and focus value curve chart (where the best-focused lens position is 76).
5.2.1 Rule-based search result

Fig. 16 shows the result of the rule-based search in the global search algorithm. The actuation method is as follows,

1. When the focus value in the lower region, the lens moves a larger step.
2. When the focus value approaches the region of the target value, the lens moves with a minimum step.
3. When the global search is completed, the lens moves to the focus position with the maximum focus value.

Therefore, quantitative moving mode results in a high moving frequency and longer moving time, which does not meet the timely demand of AF.

5.2.2 Fuzzy search result

Fig. 17 shows the search result of the fuzzy controller. As seen, the moving frequency is decreased obviously. The actuation method is as follows,

1. The distance of the moving step of the lens is determined by fuzzy inference. When the focus value is in the lower region, the moving step is larger.
2. When the focus value approaches the target value, the moving step is smaller.

The result is better because of the non-quantitative movement.
5.2.3 Fuzzy sliding-mode search result

Fig. 18 shows the search result of the fuzzy sliding controller. The complexity of the fuzzy controller is greatly decreased because of the combination of sliding plane surface, thus further obtaining the optimal parameters combination of membership functions and control rule. As a result, better execution efficiency can be achieved, and the positive and reversal rotation frequency can be minimized. As the total moving distance is minimized, the total time spent is also shortened.

5.2.4 Comparison of experimental result

The experimental result shown that, the frequency of the rule-based search is 17-24 times, and each focus search can be finished in 20.7 times on an average. The search frequency of fuzzy control is 3-8 times, and the focusing can be finished in 7.1 times on an average. The search frequency of fuzzy sliding control is decreased to 2-7 times, and the focusing can be finished in 5.3 times on an average. The statistical results of the experiment are shown as Table 3. As seen, the rapid AF can be realized by the proposed AF search algorithm.

<table>
<thead>
<tr>
<th>Methods</th>
<th>Times</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
</tr>
<tr>
<td>Rule-based search (traditional approach)</td>
<td>20.7</td>
</tr>
<tr>
<td>Fuzzy controller</td>
<td>7.1</td>
</tr>
<tr>
<td>Fuzzy sliding-mode controller</td>
<td>5.3</td>
</tr>
</tbody>
</table>

6. CONCLUSIONS

Although AF technology has been applied to electronic imaging products in recent years, the focus-searching mode is unsatisfactory with excessive motor rotation for adjusting the lenses, thereby lengthening the search path and increasing the search time. Therefore, this paper proposed a fuzzy sliding-mode controller, which integrates the advantages of fuzzy controller and sliding surface to achieve AF with CMOS image sensing module. The advantage of fuzzy controller is that it does not require systematic mathe-
atical model, but the setting of some parameters relies on trial-and-error for adjustment. Hence, it is time-consuming if the system is complex or has high demand for control. In some cases, the control results are unsatisfactory due to lack of experience in operation. Therefore, this research proposed to replace the original input variables of the fuzzy controller MTF and dMTF with sliding surface to reduce the complexity of control rule. The application proved that the AF module designed by this paper can search the focus of the lens rapidly, so as to capture sharp images.

REFERENCES


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