JOURNAL OF INFORMATION SCIENCE AND ENGINEERING 26, 1261-1272 (2010)

An Efficient Auto Focus Method for Digital Still Camera Based on Focus Value Curve Prediction Model

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This paper models focus value curve from point light source to focus measure calculation. This model shows that focus values of one object in a scene will form a single peak bell-shaped curve in camera. Our proposed auto focus method adopts this model with focus sub-window selection to predict the peak of focus value curve. Accurate prediction for the best-focused lens position will greatly shorten search time. Besides, the period of focus value feedback from camera chip is further considered to determine lens step in one period to optimize practical time consumption. Through experiments, our model for focus value curve is correct and proposed auto focus method efficiently shortens overall search time.

Keywords: focus value curve, focus measure, auto focus, sub-window, best-focused lens position

1. INTRODUCTION

The demand of digital still cameras grows gradually in the past years worldwide. Auto exposure (AE), auto white balance (AWB), and auto focus (AF) are the three key technologies to control the image quality in the low cost and high quality digital camera market. Auto focus mainly aims to search for the best-focused lens position. A dedicated sensor for distance detection is usually adopted in the high end single-lens reflex (SLR) cameras. To lower cost, the secondary focusing sensor is always unavailable in the low cost consumer market so various auto focus methods are proposed to speed up search time and increase focusing accuracy.

Exhaustive mountain climbing method (EMC) [1, 2] scans image focus values step by step from the start to the end lens position. EMC is the most accurate auto focus algorithm due to search for each lens position but time consumption is its major shortcoming. Adaptive step size mountain climbing method [3] reduces search steps by dynamic lens step selection and can effectively reduce the search time of EMC. Though it performs well theoretically, implementation of this method has many limitations in practice. For example, lens step size in one period will be constrained by the period of focus value feedback from camera chip.

In addition to search methods, various focus measure filters are designed to increase accuracy and shorten the search time for the best-focused position. C. H. Park *et al.* [4] designed a new filter with fewer coefficients to reduce time consumption of focus measure calculation and keep high search accuracy. J. H. Lee *et al.* [5] proposed a two-stage search algorithm with different filters to avoid sidelobe problem and further enhance

Received June 10, 2008; revised October 27, 2008; accepted November 12, 2008.
Communicated by H. Y. Mark Liao.

accuracy. Additional hardware design is necessary to achieve above methods, and cost will be increased unfortunately.

This paper derives focus value curve model from point spread function and we propose a predictive auto focus method using our model. Only few lens positions should be checked to predict the peak of focus value curve. Section 2 discusses the relation between optical system and focus measure calculation of camera chip. Practical overall search time and lens motor rotation rate will be also explored in this section. Detailed proposed auto focus method will be described in section 3. Section 4 verifies our auto focus method and demonstrates the performance in our prototype camera, and followed by the conclusions and future works in section 5.

2. FOCUS VALUE CURVE FORMULATION AND TIME CONSUMPTION EVALUATION

In past experience, it is observed when an object is focused at a fixed distance, focus value curve is always formed as a bell-shaped curve shown in Fig. 1 (a) and the peak of this curve is the best-focused lens position. If more than one object appears in a scene, there will be more than one peak in the focus value curve, such as demonstration in Fig. 1 (b). This section describes focus value curve formation from a single object in a scene and also shows that multi-peaks focus value curve is the combination of single peak curve from a single object. Noise effect from image sensor output and the relation between lens motor and focus filters are also explored in this section.

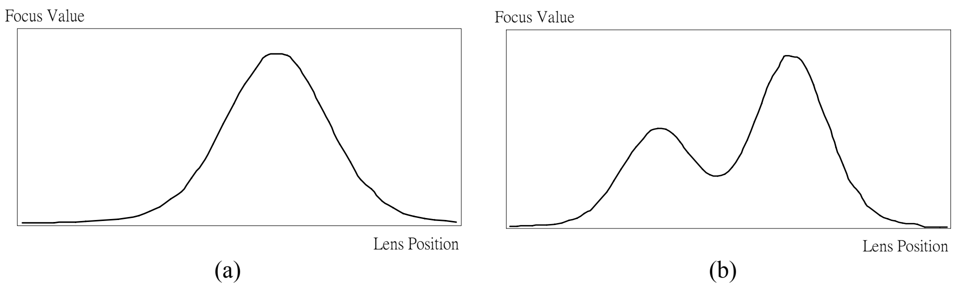


Fig. 1. (a) Focus value curve of a single object in a scene; (b) Focus value curve of two objects in a scene.

2.1 Optical Lens System

Based on the thin-lens theorem, point light source through the lens system will be converged to a point in the best-focused position. If image plane is not located at the best-focused position, the converged point in the plane will be shaped as a circle, named as circle of confusion (CoC). Fig. 2 demonstrates the simple thin lens system and the corresponding circle of confusion. Image distance, aperture radius, and image plane location from lens are represented as q, D, and L. According to geometric optics, the radius of CoC R will be given by

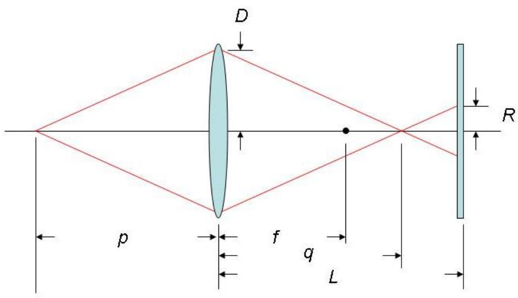


Fig. 2. Circle of confusion in an optical system.

$$R = \frac{D}{q} * |L - q|. \tag{1}$$

It is observed that R size can determine the degree of focus and smaller R represents closer to the best-focused position.

From the energy point of view, if the lens is ideal, one unit point light source is incident on the lens; the total energy through the lens system will be still one unit. Moreover the brightness will be uniform inside the circle, zero outside. The response of lens system for point light source is called point spread function (PSF); the ideal point spread function [6] will be represented as

$$\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} h_{ideal}(x, y)dxdy = 1 \tag{2}$$

with

$$h_{ideal}(x, y) = \begin{cases} \frac{1}{\pi R^2} & \text{if } x^2 + y^2 \le R^2 \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

where R is the radius of CoC. However, the real lens system is not ideal and practical point spread function [6] will be modified as

$$h_G(x, y) = \frac{1}{\sqrt{\pi R^2}} e^{-\frac{x^2+y^2}{R^2}}. \tag{4}$$

Now we can demonstrate the image through the lens system as

$$G(x, y) = I(x, y) * h_G(x, y) \tag{5}$$

where $I(x, y)$ is the original image, $G(x, y)$ is the image through the lens system and * is the convolution operator. From Eq. (5), it shows that the lens system can be regarded as an optical blur system.

2.2 Focus Value Curve

Sharpness implies the high frequency components of an image so high pass filters are often used to extract high frequency portions of an image. In our formulation, image gradient, first partial derivative of an image, is used to extract high frequency components, and squared gradient is adopted as focus value calculation. Let $G(x, y)$ be the blurred image through the lens; then, the image gradient will be given by

$$\nabla G(x, y) = \begin{bmatrix} \nabla G_x \\ \nabla G_y \end{bmatrix} = \begin{bmatrix} \dfrac{\partial G(x, y)}{\partial x} \\ \dfrac{\partial G(x, y)}{\partial y} \end{bmatrix} \tag{6}$$

and focus value (FV) is represented as

$$FV = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} [\nabla G_x]^2 \, dxdy + \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} [\nabla G_y]^2 \, dydx. \tag{7}$$

Assume that the original image in Eq. (5) is point light source, *i.e.* Dirac delta function. Eq. (7) can be simplified as

$$\begin{aligned} FV &= \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \frac{4x^2}{\pi R^6} e^{-\frac{2(x^2+y^2)}{R^2}} \, dxdy + \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \frac{4y^2}{\pi R^6} e^{-\frac{2(x^2+y^2)}{R^2}} \, dydx \\ &= \frac{1}{\sqrt{2\pi} R^3} \left(\int_{-\infty}^{\infty} e^{-\frac{2y^2}{R^2}} dy + \int_{-\infty}^{\infty} e^{-\frac{2x^2}{R^2}} dx \right) \end{aligned} \tag{8}$$

due to geometric symmetry. Focus value equation can be further calculated as

$$FV = \frac{1}{R^2} \tag{9}$$

using Eqs. (10) and (11)

$$\int_{-\infty}^{\infty} e^{-ax^2} dx = \sqrt{\frac{\pi}{a}} \tag{10}$$

$$\int_{-\infty}^{\infty} x^2 e^{-ax^2} dx = \frac{1}{2a}\sqrt{\frac{\pi}{a}}\ . \tag{11}$$

From Eq. (1), R is represented by the combination of image distance, aperture radius, and image plane location. Eq. (9) can be given by

$$FV = \frac{q^2}{D^2 \left| L - q \right|^2}\ . \tag{12}$$

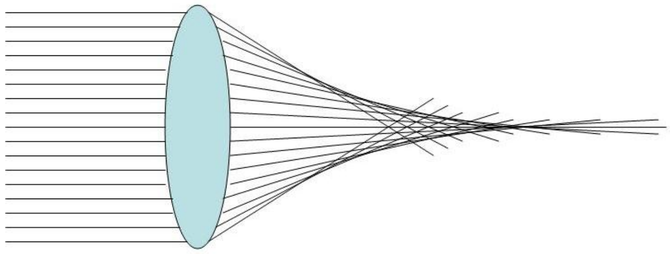


Fig. 3. Optical aberration in a thick lens system.

Eq. (12) is obtained under the hypothesis of ideal thin lens. In reality, lens system is not a thin lens and has optical aberration in Fig. 3. Point light source through the lens system never forms a point with zero radius size. It means that the radius of CoC will be converged into a minimum size larger than zero, so focus value could be concluded as

$$FV = \frac{c_1}{k + |x - x_0|^2}, \tag{13}$$

where

c_1: a constant to fit parameter $(\frac{q^2}{D^2})$
x: to fit the lens position (L)
x_0: to fit the best-focused lens position (q)
k: a constant denoting minimum radius of CoC

Eq. (13) shows that a single object through the lens will form a bell-shaped curve in focus value calculation. It is also obvious that aperture size and optical aberration of the lens system will be regarded as constants and only adopted high pass filters will affect the power of focus value curve.

Based on above discussion, focus value curve of multi-objects in different distances can be expressed as

$$FV = \sum_{i=1}^{n} \frac{c_i}{k_i + |x - x_i|^2}, \tag{14}$$

where i is the number of objects in a scene. Eq. (14) is the generalization form of Eq. (13) and demonstrates that multi-objects in a scene will form multi-peaks focus value curve.

2.3 Noise Effect and Focus Value Ratio

The scheme of image calculated as focus measure is described in Fig. 4 [7] and it shows that blurred images through the lens will be measured in chip with additive noise. This additive image noise is additional vibration so it will affect focus measure calculation more in low focus value area than in high focus value area of curve. It means that flat area of focus value curve should not be considered into prediction process to boost search accuracy. Define focus value ratio r as

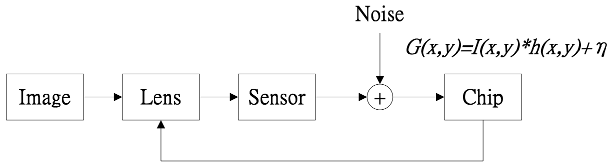


Fig. 4. Scheme of image calculated as focus value.

Table 1. Relation between focus value curve and focus value ratio.

$1 \leqq r < n$	$r \geqq n$	$r < 1$
Flat area	Rising area	Falling area

$$r = \frac{current\ focus\ value}{last\ focus\ value}. \tag{15}$$

Table 1 shows the relation between focus value curve and focus value ratio: $1 \leqq r < n$ represents flat area of curve; $r \geqq n$ represents rising area of curve; and $r < 1$ represents falling area of curve. In our method, only $r \geqq n$ or $r < 1$ focus values will be recorded and $1 \leqq r < n$ focus values will be discarded. Experiments show that $n = 5$ gives satisfactory results in most cases.

Focus value is the focus measure summation of all pixels so focus value curve will be affected by accumulation of sensor noise. In order to further reduce noise effect, a noise threshold is defined to exclude noise from focus measure accumulation. Image gradient calculated in Eq. (6) below this threshold will not be counted into focus value summation in Eq. (7). Focus value curve with and without noise threshold are demonstrated in Fig. 5. It is clear that focus value curve is smoothed by noise threshold and has better approximation with real focus measure summations.

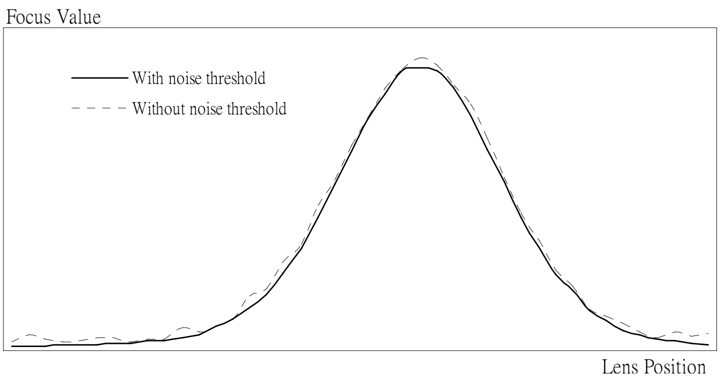
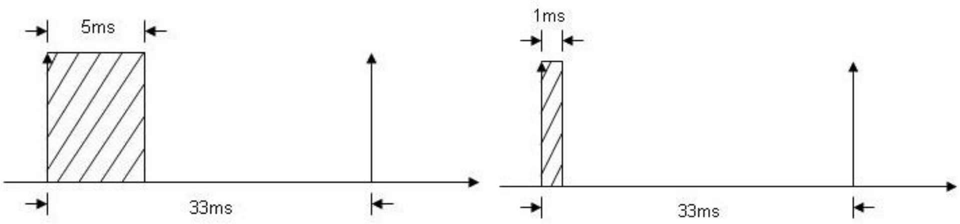


Fig. 5. Focus value curve with threshold and without threshold.

2.4 Lens Step versus Motor Rotation Rate

Image focus measure is periodically calculated and its feedback frequency is limited by image sensor capability. In general, the feedback period, no matter for complementary metal oxide semiconductor (CMOS) or charge-coupled device (CCD) sensor, will at least match refresh rate in preview, for example, 30 frames per second, *i.e.* 33 milliseconds per period.

Lens motor rotation rate is a significant issue which should be considered into time consumption evaluation. One motor with 200 pulses per second (pps) takes five milliseconds per step, but another motor with 1000pps only takes one millisecond per step. In Fig. 6, no matter 200pps or 1000pps motor is adopted; it will take 33 milliseconds if only one step is moved in one period. These two motors, 200pps and 1000pps motor rotation rate, will have maximum six and thirty lens steps in one period. EMC moves one step in a period and takes much time to wait for next accumulated focus value. To reduce waiting time, the consideration for lens step and rotation rate is a key point to enhance overall search time.



(a) (b)

Fig. 6. (a) One step of 200pps lens in one period; (b) One step of 1000pps lens in one period.

3. OUR PROPOSED PREDICTIVE AUTO FOCUS ALGORITHM

From the discussion in section 2, we know that the real focus value curve will form a multi-peaks curve because there is usually more than one object appeared in the real scene. Traditional search methods will make the highest focus value in multi-peaks curve as the best-focused lens position. It means that the object with most details will be regarded as the most significance in a scene. But the object with the most details is usually not the focused object in current auto focus system. Face-detection auto focus is an example. Human face is always recognized before focus and regarded as the most important feature in the scene. User-defined target auto focus is another example. So focused object is always pre-picked from the scene and is searched for the best-focused lens position. In the point of view, one selected sub-window from multi-AF-windows is the unique focus window during the auto focus and focus value curve of this sub-window will form a single peak curve. Our method employs auto focus based on sub-window selection and the details of proposed method are described as follows.

The complete scheme of our proposed method is demonstrated in Fig. 7. First of all, Eq. (13) is our modeled focus value curve with image gradient focus filter. The modeled equation will not be altered during overall search unless focus filter is changed. To well utilize the waiting time of focus value feedback period, *m* lees steps in one period is determined by motor rotation rate. Noise threshold is defined in this stage to reduce noise effect in focus value accumulation. These pre-defined parameters are constants during overall search. Besides parameter initialization, the sub-window should be selected before

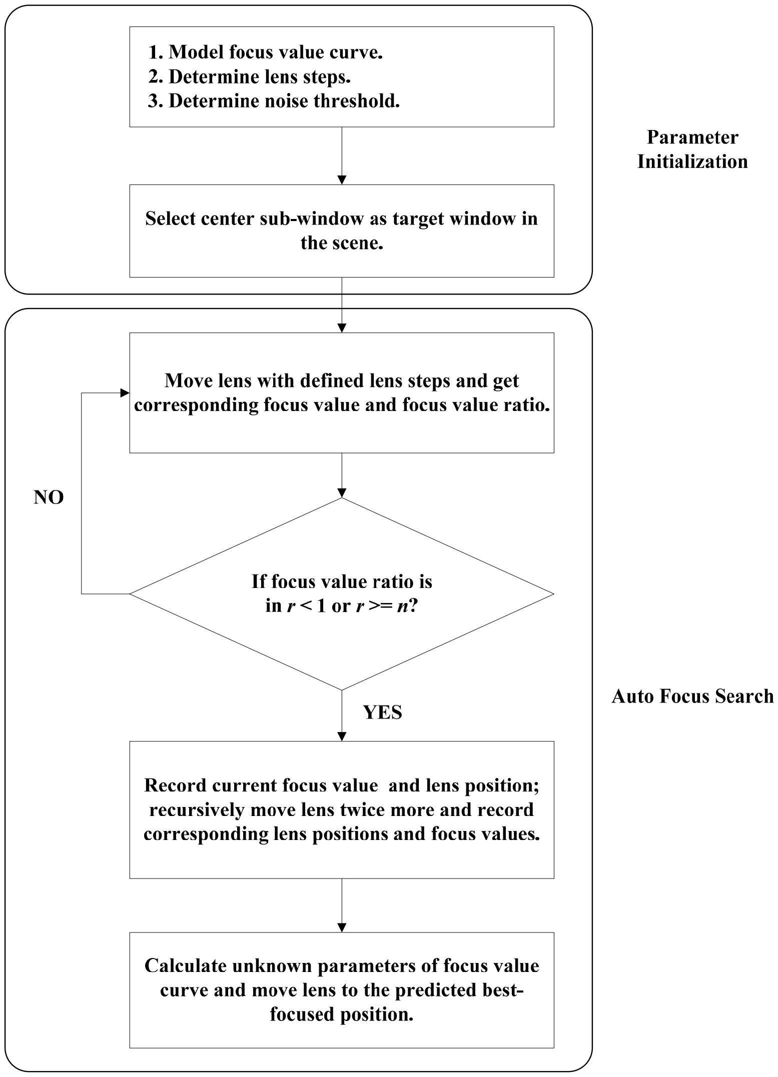


Fig. 7. Scheme of our proposed method.

focus search. Complex object recognition is a big topic and not discussed in this paper. In our proposed method, the center sub-window is chosen as the target window because users usually regard image center as the most significant portion in a scene.

Practical focus search is employed after parameter initialization. Lens is moved by predefined m steps in one period and camera chip calculates focus value of sub-window and corresponding focus value ratio. If focus value ratio is located at $1 \leqq r < n$ domain, current lens position is far from the best-focused position and lens should be moved with m steps again. When focus value ratio $r \geqq n$, lens position approaches the curve peak and current focus value and lens position should be recorded. After $r \geqq n$, lens is moved with m steps twice and corresponding focus values and lens positions are recorded even if focus value ratio $r < 1$, the falling area in curve. Three focus values and lens positions are obtained up to now and parameters, c_1, k, and x_0, of Eq. (13) can be calculated. The predicted best-focused lens position is located at position x_0 and overall search procedure is completed after lens is moved to the predicted position.

4. EXPERIMENT

In this section, proposed auto focus method is employed in our prototype camera in Fig. 8. Our prototype system carries out full functions of digital cameras including a six mega pixel CCD sensor, image signal processing chip, 5X optical zoom lens with 200pps rotation rate motor, 2.5″ LCD, and USB *etc*.

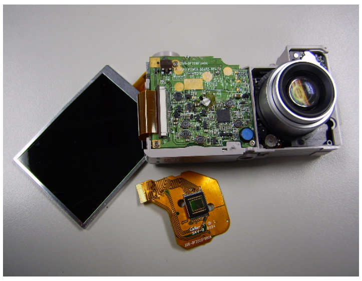
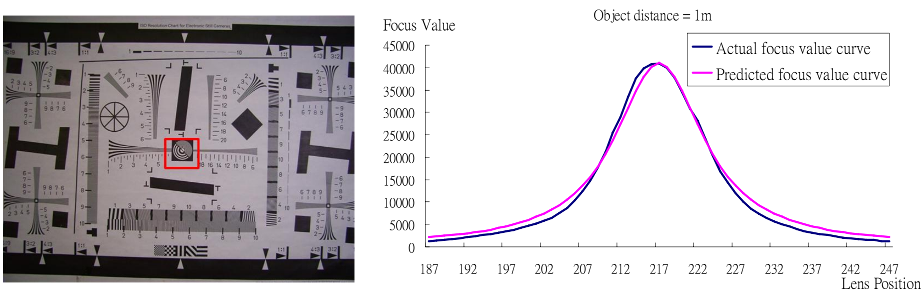


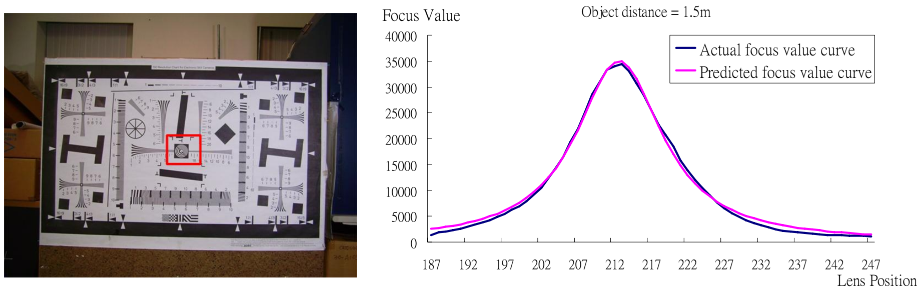
Fig. 8. Prototype camera with full functions.

In this prototype camera, image gradient focus filter is used to calculate and accumulate focus measure and Eq. (13) is our modeled focus value curve. Lens steps are defined as six because of 200pps lens rotation rate. Noise threshold is chosen as 60 to reduce noise jitter and smooth the curve. This threshold value gives satisfactory results in most scenarios in our prototype camera. Center sub-window is the target window to accumulate focus measure. Objects with three different distances are searched by our method. Figs. 9, 10, and 11 show actual focus value curves and predicted curves with three calculated parameters of Eq. (13). These solved parameters are listed in Table 2. Table 3 shows overall time consumption of exhaustive mountain climbing, our proposed



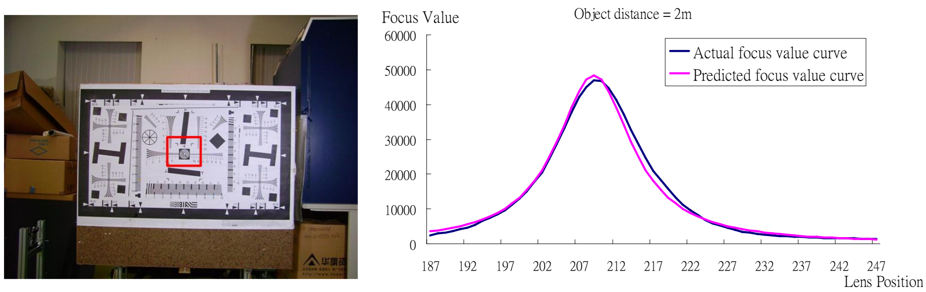
(a) (b)

Fig. 9. (a) Object with one meter distance; (b) Actual and predicted focus value curves.



(a) (b)

Fig. 10. (a) Object with 1.5 meter distance; (b) Actual and predicted focus value curves.



(a) (b)

Fig. 11. (a) Object with two meter distance; (b) Actual and predicted focus value curves.

Table 2. Calculated unknown parameters.

Object Distance (m)	c_1	k	x_0
1.0	2049531	50	217
1.5	1799572	51	213
2.0	1840199	38	209

Table 3. Time consumption of three methods.

Search Algorithms	1.0m	1.5m	2.0m
EMC	1028	929	797
Our Method	165	142	142
Active Focus Method	150	130	110

unit: ms

method, and active focus method [8, 9]. It is observed that proposed method takes around one-sixth time of EMC search and approaches time consumption of active focus method with additional focus sensor.

5. CONCLUTIONS AND FUTURE WORKS

We model focus value curve of a single object and find that the power of focus value equation only changes with focus filter. Although focus value curve has multi-peaks in general case, the curve will become a single peak curve through a sub-window selection because focus system usually searches for specific object. Our proposed method uses modeled curve with a center sub-window to predict the best-focused lens position in the scene. In order to reduce noise effect and smooth curve, focus value ratio and noise threshold for focus measure accumulation are introduced to enhance prediction accuracy. Lens motor rotation rate is also considered in our method to reduce lens waiting time and shorten search time further. Experiments show good results by our method in the prototype camera and time consumption of our method approaches that of active focus method.

Although our model is verified through theoretical analysis and empirical results, there are still some challenges left in the future. When sensor noise is too large, curve jitter will appear and the prediction accuracy will be decreased relatively. The sensor noise suppression for prediction accuracy is necessary to be discussed further. Besides, sub-window selection will greatly affect the accuracy of our method and it should be explored in the future.

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