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Application of fuzzy logic on astronomical images' focus measures

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Abstract: Focus accuracy is an essential factor that affects the quality of astronomical observations. The accurate measurement of celestial objects' properties depends on focus. Automatic focusing is necessary for celestial imaging systems. This paper presents a modified focus measure operator. It also proposes the use of fuzzy logic to transform images because of its tolerance of imprecise and incomplete data. The focus operators are applied to two sequences of star clusters' observations. The experimental results show that the suggested measure's overall score exceeds those of previous operators.

Key words: Autofocus, focus measure, fuzzy logic, astronomical

1. Introduction

High-quality astronomical images are necessary for astronomical research because it is highly accurate scientific work. Precise focus is one of the most significant factors that affect the quality of astronomical observations. An automatic focus system moves the CCD imaging system to the best focus position where light rays converge. Consequently, the maximum amount of light from celestial objects is concentrated into the smallest possible area at the focal plane of the CCD camera. If the imaging system is out of focus, the photons of the celestial objects will spread over a wider area of the CCD detector. As a result, the output image loses the faint objects, and this is not appropriate for scientific research.

The focus measure (FM) operator is used to determine the focus levels of a sequence of images. These images are acquired at varying distances between a camera lens and a scene object. Several operators are proposed and evaluated for microscopy images or digital photography [1, 2]. Various operators are based on transformation, such as fast Fourier transform (FFT) [3], discrete cosine transform (DCT) [4], and wavelet sum [5]. In this paper, a modified measure based on image transformation is proposed. Fuzzy logic is used as an image transformer due to its ability to deal with imprecise data.

The aim of this paper is to study the performance of several focus measure operators on astronomical images. The best focus measure operator will be used with a suitable search strategy to develop an automatic focus system for the Kottamia Astronomical Observatory (KAO). This paper is organized as follows: Section 2 presents the measures used in the performance comparison. Section 3 introduces a description of the suggested operator. Section 4 describes the used methodology. Finally, Sections 5 and 6 illustrate the experimental results and conclusion, respectively.

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2. Focus measure operators

Focus measure operators commonly use sharpness estimation, which gives a sign of the image focus level. The operators rely on different criteria such as gradient, correlation, statistics, transform, and edge. Table 1 presents operators on astronomical images of size $M \times N$ pixels used in the comparison. The selected measures are chosen based on assessments of 20 commonly used previous operators on 6 sequences of astronomical star clusters. The highest two overall scores are picked from each family.

Table 1. List of used focus measure operators.

Focus measure operator	Description
Tenengrad [6]	Calculate the sum of squares of horizontal (I_x) and vertical (I_y) image gradients using the Sobel operator. $FM = \sum_{\mathrm{M}}\sum_{\mathrm{N}}\left(\mathrm{I_x}^2 + \mathrm{I_y}^2\right)$.
Brenner [7]	Calculate the sum of the square of the difference between image intensities $(I(x,y))$ and their neighbors. $FM = \sum_{M}\sum_{N}\lvert I(x,y) - I(x+2,y)\rvert^2$.
Autocorrelation [8]	Compute the autocorrelation focus measure as $FM = \sum_{x=1}^{M-1}\sum_{y=1}^{N} I(x,y)I(x+1,y) - \sum_{x=1}^{M-2}\sum_{y=1}^{N} I(x,y)I(x+2,y)$.
Coefficient of variation [9]	Divide the standard deviation with the image mean $(\bar{I})$. $\mathrm{FM} = \frac{\left(\frac{1}{\mathrm{MN}}\sum_{\mathrm{M}}\sum_{\mathrm{N}}(\mathrm{I(x,y)} - \mathrm{I})^2\right)^{\frac{1}{2}}}{\mathrm{I}}$.
Local variance [10]	Calculate the variance of image local variance (L_v(x,y)). $FM = \frac{1}{MN}\sum_{M}\sum_{N}\left(\mathrm{L}_v(x,y) - \overline{L_v}\right)^2$. L_v(x,y) is computed as the variance of image gray-levels within a neighborhood of size $w_x * w_y$ centered at (x, y), and $\overline{L_v}$ is the mean value of L_v.
Fast Fourier transform (FFT) [3]	Calculate the sum of the absolute of the product of image magnitude and phase spectrum. $\mathrm{FM} = \sum\lvert\mathrm{Mag}(\mathrm{u,v}) \times \mathrm{Ang}(\mathrm{u,v})\rvert$.
Discrete cosine transform (DCT) [4]	Use the discrete cosine transform (DCT) to transform the image. Then calculate the sum of AC components ($\mathrm{E_{AC}}$). $\mathrm{FM} = \sum_{\mathrm{M}}\sum_{\mathrm{N}}\mathrm{E_{AC}}$.
Histogram [11]	Calculate the difference between the maximum and minimum gray-levels. $\mathrm{FM} = \max\{\mathrm{k}\vert\mathrm{P_K} > 0\} - \min\{\mathrm{k}\vert\mathrm{P_K} > 0\}$, where k is the gray-level, and P_K is the relative frequency.

3. Proposed focus measure operator

The principal objective of this paper is to study the performance of the proposed operator by using fuzzy logic as an image transformer. The motivation is to obtain a simplistic operator with a better performance. The most common operators depend on summing the pixel sharpness estimation. However, the histogram focus measure relies on computing the difference between the maximum and minimum gray-levels. The proposed operator is a modification of the histogram focus measure. To obtain improved performance, it is applied to the fuzzy logic output, as shown in Figure 1. Fuzzy logic is used to enhance the contrast of the images.

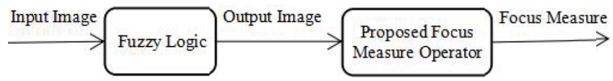


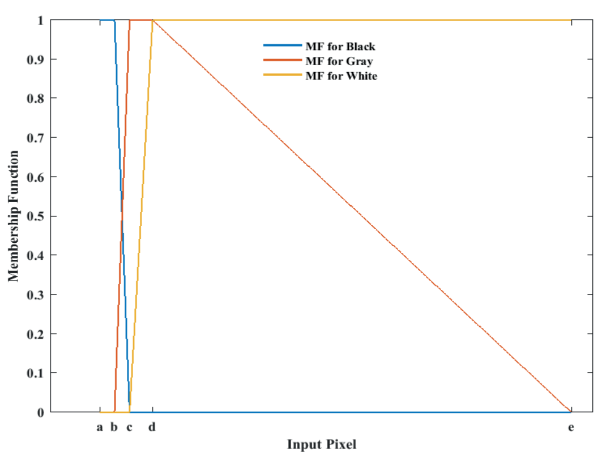
Figure 1. Proposed method block diagram.

The histogram focus measure is the difference between the maximum and minimum gray-levels. This measure supposes that the images' maxima increase as they come into focus. As a result, the difference increases between the maximum and minimum. Indeed, the image maximum may be not increased due to the effects of the observation conditions, e.g., temperature, clouds, or humidity, whereas the image minimum is assumed to be fixed since it is affected by the sky background. Therefore, another statistic should be used instead of minima to compensate for the maxima variations and guarantee that the difference increases with focus. The suggested statistic is the median of maxima. It is computed by randomly selecting samples (S_i) from the image. Then the maxima of samples are found. Finally, the median of these maxima is computed. The modified histogram focus measure is expressed as in Eq. (1), where N is the number of samples.

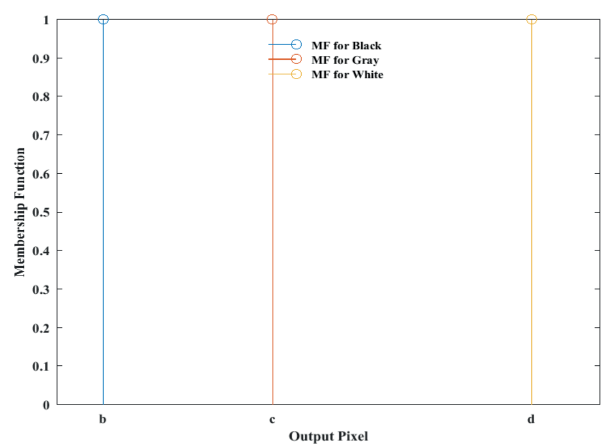
$$FM = \max\left\{\mathrm{k}|\mathrm{P_K} > 0\right\} - median\left\{\max_{(x,y)\in S_i}\{I(x,y)\}\right\}; i = 1,2,3,...,N \tag{1}$$

3.1. Fuzzy logic

Zadeh [12] introduced the concept of fuzzy logic in 1965. Fuzzy logic represents an approach of admitting to a certain degree of truth rather than the usual true or false. Fuzzy logic transforms the image data from the gray-level plane into the membership plane (fuzzification). Defuzzification is the process of mapping a membership value to a crisp value. In this paper, the adopted membership functions to the input and the output of the single-input-single-output system are trapezoids and singletons, respectively, as shown in Figure 2a and Figure 2b, respectively.



(a)



(b)

Figure 2. Input and output membership functions: (a) input membership function, (b) output membership function.

The trapezoidal functions are given as follows:

$$\mu_{black} = \begin{cases} 0, & p \le a \\ 1, & a \le p \le b \\ \frac{c-p}{c-b}, & b \le p \le c \end{cases} \tag{2}$$

$$\mu_{gray} = \begin{cases} 0, & p \leq b \\ \frac{p-b}{c-b}, & b \leq p \leq c \\ 1, & c \leq p \leq d \\ \frac{e-p}{e-d}, & d \leq p \leq e \end{cases} \tag{3}$$

$$\mu_{white} = \begin{cases} 0, & p \leq c \\ \frac{p-c}{d-c}, & c \leq p \leq d \\ 1, & d \leq p \leq e \end{cases} \tag{4}$$

Here, μ is the membership function, p is the pixel value, a is the image minimum, b is the mean of minima, c is the median of maxima, d is the mean of maxima, and e is the image maximum. The minima mean and maxima mean are expressed as in Eqs. (5) and (6), respectively.

$$b = \frac{1}{N}\sum_{i=1}^{N} \min_{(x,y)\in S_i}\{I(x,y)\} \tag{5}$$

$$d = \frac{1}{N}\sum_{i=1}^{N} \max_{(x,y)\in S_i}\{I(x,y)\} \tag{6}$$

The proposed fuzzy system uses the following rules:

- IF p is dark (black), THEN make it darker.
- IF p is gray, THEN make it gray.
- IF p is bright (white), THEN make it brighter.

The crisp value (fuzzy logic output image) is given as in Eq. (7).

$$Crisp = \frac{\mu_{black} \times b + \mu_{gray} \times c + \mu_{white} \times d}{\mu_{black} + \mu_{gray} + \mu_{white}} \tag{7}$$

4. Methodology

The proposed method is tested with two different two-star cluster sequences. The two clusters are M39 and N7067. The two sequences are observed by an imaging system based on the 74-inch telescope of the Kottamia Astronomical Observatory and a CCD camera system [13]. Each sequence contains in-focus and out-of-focus frames. The two sequences, M39 and N7067, consist of 51 and 55 images, respectively. The images are of size 2048 × 2048 pixels. The suggested method's performance is compared to that of the operators mentioned in Section 2. Various ranking criteria are used in the literature for the comparison of focus measures. The focus measure operators were ranked according to their scores in [11]. These scores are obtained based on four criteria, which are: (1) accuracy, the difference between the optimum focus position obtained using the focus measure operator and the best focus position; (2) range, defined as the distance between two neighboring local minima around the global maximum; (3) number of false maxima, described as the number of spurious maxima appearing in a focus measure curve (focus measure versus focus position); and (4) width, given as the width of the focus measure curve at half of its height. Here, the focus measure score is given by summing the four individual criterion values after normalizing them, as in Eq. (8).

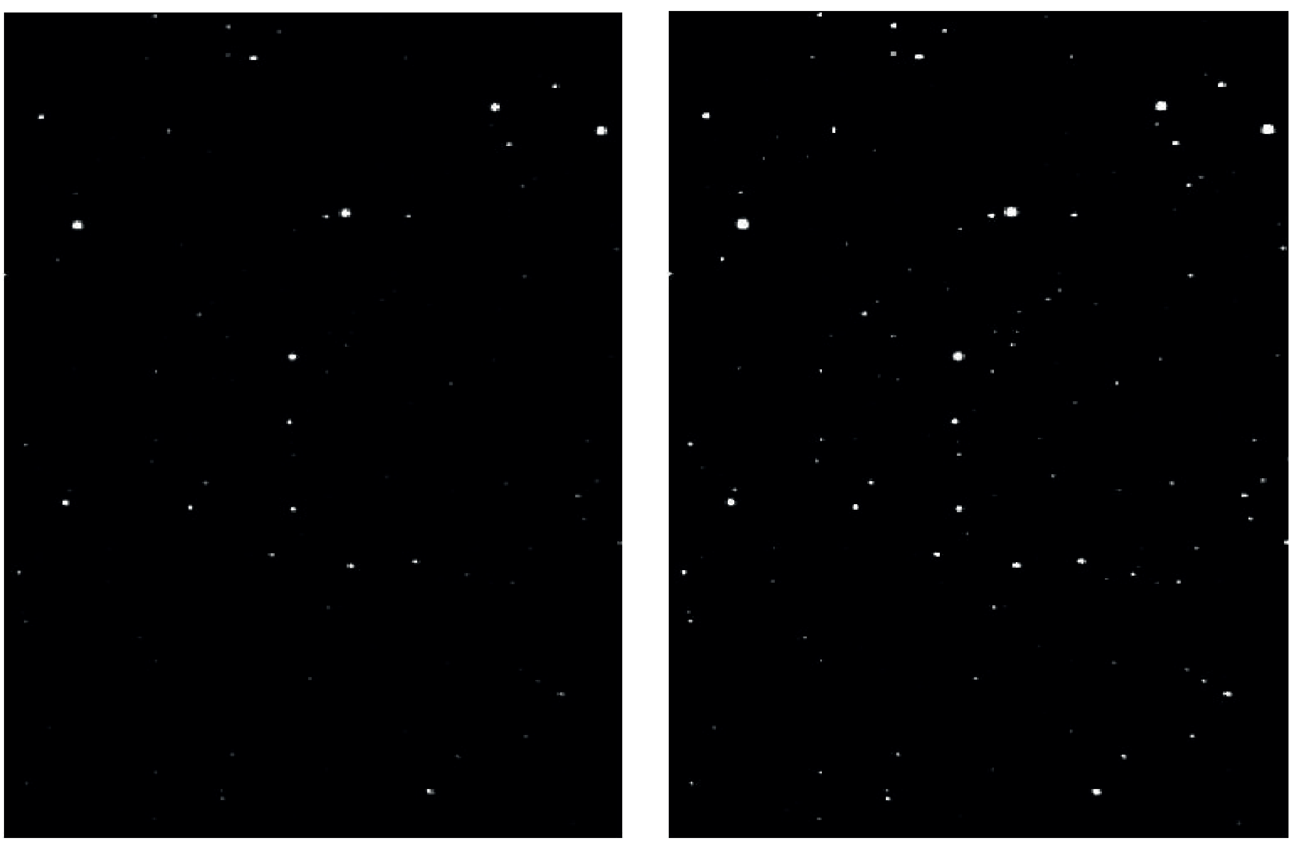
$$Score_i = \frac{a_i}{\max(a_i)} + \frac{r_i}{\max(r_i)} + \frac{fm_i}{\max(fm_i)} + \frac{w_i}{\max(w_i)} \tag{8}$$

Here, i = 1,...,n, n is the number of the focus measure operators; a_i is the accuracy of the focus measure operator; r_i is the range of the focus measure curve; fm_i is the number of false maxima that appear in the focus measure curve; and w_i is the width of the focus measure curve.

5. Experimental results and discussion

Contrast enhancement is one of the principle applications of image transformation. This paper studies the effects of contrast enhancement using fuzzy logic on the focus measure. Figures 3a, 3b, 4a, and 4b show representative examples of the fuzzy logic input and output images for sequences M39 and N7067, respectively. Transformation using fuzzy logic improves the sharpness of the image and enhances the faint details appearing.

Tables 2 and 3 present the obtained results of the two sequences, M39 and N7067, respectively. The experimental results show that the modified histogram and local variance focus measures have the highest rank or the lowest score for the M39 and N7067 sequences, respectively. It should be mentioned that the coefficient



(a) Input image. (b) Fuzzy logic output image.

Figure 3. A representative example of sequence M39: (a) input image, (b) fuzzy logic output image.


(a) Input image.


(b) Fuzzy logic output image.

Figure 4. A representative example of sequence N7067: (a) input image, (b) fuzzy logic output image.

of variation and local variance almost have the highest ranks of the M39 and N7067 sequences, respectively. Meanwhile, the two measures almost have the lowest ranks of the N7067 and M39 sequences, respectively.

Table 2. The rank summary for sequence M39 of different measures.

Name	Accuracy	Range	No. of false	Width	Score
Modified histogram	0	0	0	1897.1	0.99793
Coefficient of variation	0	0	0	1901.1	1
DCT	0	2000	1	1227.6	1.3003
Tenengrad	0	2000	2	1105.3	1.436
Brenner	0	2000	2	1118.1	1.4427
Autocorrelation	0	2000	2	1126	1.4468
FFT	0	4200	2	1592.8	2.1924
Local variance	0	4200	5	597.86	2.269
Histogram	0	4400	5	1558.7	2.8199

Table 4 presents the overall rank/score of the two sequences. The sum of the scores of the individual measures produces the overall score. The results show that the proposed modified histogram is the best measure.

Table 3. The rank summary for sequence N7067 of different measures.

Name	Accuracy	Range	No. of false	Width	Score
Local variance	0	2600	2	1060.5	1.1802
Tenengrad	0	2600	3	2078.3	1.6434
Modified histogram	0	2600	2	2742.6	1.7392
Brenner	0	2600	4	2133.11	1.7867
Autocorrelation	0	2600	4	2237.4	1.8213
FFT	0	2800	4	2648.1	2.0022
DCT	400	4500	4	2195.9	2.8012
Coefficient of variation	700	2600	8	2919.9	3.5481
Histogram	700	3500	7	3009.1	3.6528

Table 4. The overall rank summary of different measures.

Name	M39	N7067	Overall score
Modified histogram	0.99793	1.7392	2.73713
Tenengrad	1.436	1.6434	3.0794
Brenner	1.4427	1.7867	3.2294
Autocorrelation	1.4468	1.8213	3.2681
Local variance	2.269	1.1802	3.4492
DCT	1.3003	2.8012	4.1015
FFT	2.1924	2.0022	4.1946
Coefficient of variation	1	3.5481	4.5481
Histogram	2.8199	3.6528	6.4727

6. Conclusion

The quality of astronomical observations varies with focus. This paper discusses the effect of fuzzy logic on astronomical images' focus measures. The proposed fuzzy logic enhances the contrast. Then a modified focus measure is applied to the enhanced image. The paper includes a performance evaluation of the mentioned measures. The operators are applied to two sequences of star cluster images. The experimental results show that the proposed modified histogram achieves the highest overall score.

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