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Performance Metrics for Passive Auto-Focus Search Algorithms in Digital and Smart-Phone Cameras

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Abstract. *Passive autofocus (AF) is a key component of many digital and high megapixel smart-phone camera systems. In order to make informed choices in the selection of a passive AF search algorithm, it is essential to utilize sound performance metrics. The performance metrics currently employed do not take into account all facets involved in passive AF systems. In this article, five performance metrics are proposed to be simultaneously evaluated in order to accurately reflect all aspects of a passive AF system including focusing speed, accuracy, power consumption, and user experience. Experimental results on a prototype digital camera platform for four representative AF search algorithms are presented to show how to carry out the evaluation of any passive AF search algorithm. © 2011 Society for Imaging Science and Technology.*
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INTRODUCTION

In order to gain market share in the growing digital and smart-phone camera markets, camera manufacturers must continually add and improve existing features to their latest product offerings.[1,2] Autofocus (AF) is one such feature, whose aim is to enable consumers to quickly take pictures with little or no manual intervention in adjusting the camera's focus.

While AF has been a standard feature in digital and cell-phone cameras, consumers often complain about their cameras' slow AF performance, which ultimately leads to missed picture opportunities, rendering valuable moments and events with undesired out-of-focus pictures.

There are two main approaches to realize AF: active AF and passive AF. Active AF employs the use of external infrared or ultrasound sensors to determine the distance between the camera and an object of interest in front of the camera. As an alternative to active AF, camera manufacturers often make use of the simpler passive AF approach where a measure of image sharpness is extracted from a portion of the captured image via the camera's image signal processor (ISP). This measure is then used to adjust the imaging distance via a search algorithm running as a software feedback control loop on the processor so that the extracted measure obtains a peak value. Owing to its ease of integration into digital hardware and software, the passive AF approach has become the *de facto* standard in realizing the AF feature for compact consumer digital or camera phone systems.

This article discusses how the performance of a passive AF system can be evaluated comprehensively based on the simultaneous analysis of five metrics which take into account AF speed, accuracy, power consumption, and user experience. The existing literature on AF for digital cameras has primarily characterized AF performance using metrics which only measure speed and accuracy,[3,4] while neglecting the increasingly important aspects of power consumption and user experience. Experimental results obtained from simulation results on real-world focus sequence scene data taken with a prototype digital camera system reveals the usefulness of these metrics for comparing the AF performance of passive AF search algorithms.

The rest of this article is organized as follows. The next section provides an overview of a passive AF systems model. The proposed set of AF performance metrics is then discussed in terms of the model. To judge the usefulness of the set of metrics, a set of representative algorithms from the vast amount available is necessary. An overview of existing popular AF search algorithms is provided and four representative algorithms are selected for performance evaluation. Experimental results comparing the performance of the four selected search algorithms are then presented, and finally the conclusions are stated.

AF SYSTEM MODEL

Figure 1 illustrates a high-level overview of a passive AF system typically implemented in a digital or smart-phone camera device.[1] As illustrated, the input to the AF system is normally a draft preview color filter array (CFA) image, where the image sensor is set to the draft preview mode. The draft preview mode provides a down-sampled version of the full resolution image off the image sensor in order to be able to drive the sensor at higher frame rates (e.g., at least 30 frames-per-second) and enable a real-time AF operation.

This reduced size image gets processed by an image signal processor (ISP) to extract the AF statistics or sharpness information from a prespecified portion of the image known

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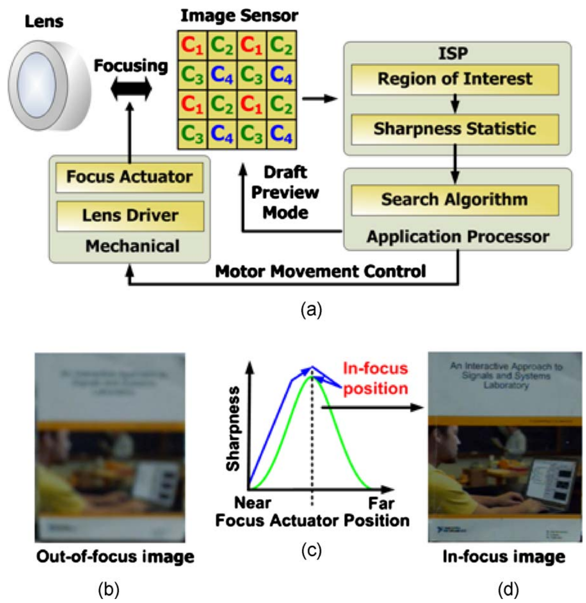

Figure 1. Overview of passive AF system: (a) feedback control loop, (b) out-of-focus scene before AF, (c) sharpness function and "stop-at-peak" search algorithm movement, and (d) in-focus image captured with in-focus position determined by AF.

as the focus region. This sharpness information is then passed to a search algorithm which decides the amount of the focus actuator movements needed to bring the image closer into focus at the next iteration of the feedback control loop. The search process continues until the peak location of sharpness (i.e., the in-focus position) is passed by a few focus actuator steps, at which point, the actuator can be moved back to the determined in-focus position.

Figure 2 illustrates a mathematical model of such a passive AF system. This model provides the notation needed to succinctly define the AF performance metrics which are discussed in the following section.

Let $f(\mathbf{n}^{(k^*)})$ denote the blur-free, Bayer-pattern sampled image and $h_{PSF}(\mathbf{n}^{(k)})$ denote the point spread function (PSF) of the camera lens. Let $y(\mathbf{n}^{(k)})$ denote the noise-free, blurred, Bayer-pattern sampled image within a focus region or window, and $z(\mathbf{n}^{(k)})$ denote a zero-mean, additive white Gaussian noise term which is considered to be independent of the signal and lens position, with a standard deviation of σ_z. The index vector is defined as $\mathbf{n}^{(k)}=[n_1 \;\; n_2 \;\; n_3^{(k)}]^{\mathrm{T}}$ where the indices n_1 and n_2 represent discrete spatial positions (row and column, respectively) in the two-dimensional (2D) image plane, and the index $n_3^{(k)}$ represents the focus actuator position at the kth iteration in the search algorithm.

The noisy observation $y_z(\mathbf{n}^{(k)})$ is then subjected to spatial frequency analysis via an AF digital bandpass filter with spatial impulse response of $h(\mathbf{n}^{(k)})$ for the purpose of extracting focus values $F(n_3^{(k)})$ (output energies of the AF filter integrated over the focus region). The purpose of an AF search algorithm is to locate the focus actuator position at which F is maximized, that is $n_3^{(k^*)}$.

It should be noted that the above model incorporates any digital filter or sharpness function one may wish to use when designing a passive AF system. The subject of sharpness function performance evaluation and selection has been extensively studied in the existing literature[5–7] and is not a primary issue of concern here, since this article addresses a framework for the performance evaluation of the inherent AF search algorithm regardless of the sharpness function or digital filter chosen.

AF PERFORMANCE METRICS

The performance of any passive AF search algorithm can be characterized by simultaneous analysis and evaluation of the following five metrics over a set of real-world AF field test data: (i) total number of iterations (TNI) (ii) total distance moved (TDM), (iii) offset from truth (OFT), (iv) in-focus position overrun (IPO), (v) total number of direction changes (TNDC), which are defined as follows:

$$\mathrm{TNI} = K, \tag{1}$$

$$\mathrm{TDM} = \sum_{k=0}^{k-2} |n_3^{(k+1)} - n_3^{(k)}|, \tag{2}$$

$$\mathrm{OFT} = |n_3^{(K-1)} - n_3^{(k^*)}|, \tag{3}$$

$$\mathrm{IPO} = |n_3^{(k-2)} - n_3^{(k^*)}|, \tag{4}$$

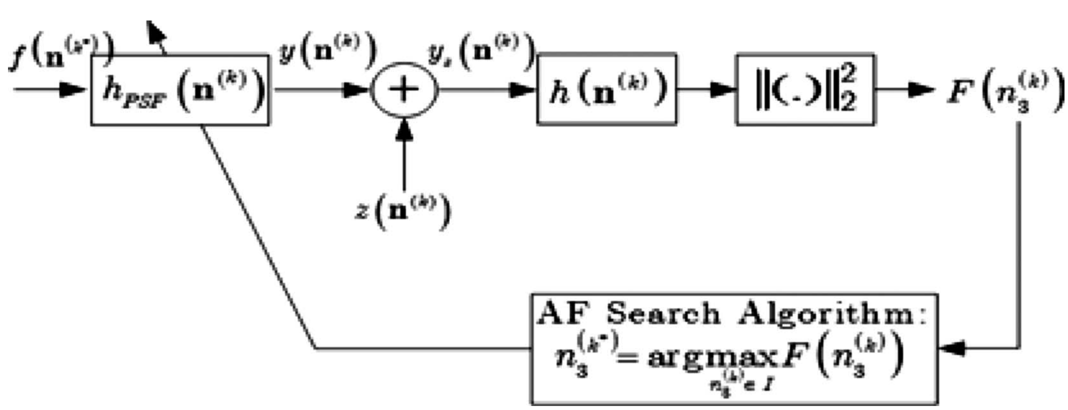

Figure 2. Passive AF system model used in the definition of the AF search algorithm performance metrics.

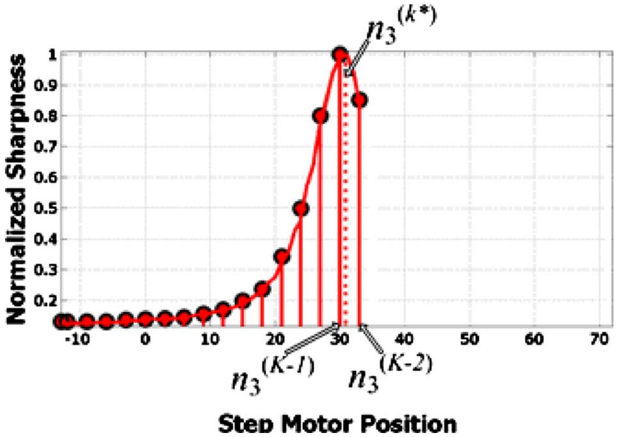

Figure 3. True, $n_3^{(k^*)}$, and estimated, $n_3^{(K)}$, in-focus positions in AF search algorithms.

$$\mathrm{TNDC} = 0$$

$$\mathrm{TNDC} = \begin{cases} \mathrm{TNDC}++ & \begin{array}{c}[(n^{(k)} > n^{(k-1)}) \wedge (n^{(k+1)} < n^{(k)})] \vee \\ [(n^{(k)} < n^{(k-1)}) \wedge (n^{(k+1)} > n^{(k)})]\end{array} \\ \mathrm{TNDC} & \text{other} \end{cases}, \quad (5)$$

where K indicates the count corresponding to the total number of iterations expended by the AF search algorithm, $n_3^{(k^*)}$ is the true in-focus position [normally determined by a global search (GS) method], $n_3^{(K-1)}$ is the final estimated in-focus position, and $n_3^{(K-2)}$ is the position corresponding to one iteration before moving to the final estimated in-focus position. A depiction of these three focus actuator positions is provided in Figure 3. Past attempts at AF search algorithm performance evaluation have typically centered around comparisons using speed and accuracy, while usually neglecting power consumption and user experience measures.[3,4] There is little, if any, research on AF search algorithm performance evaluation in the open literature, where most AF related papers cover the other topics of focus or sharpness measure evaluation[5–7] and neglect the equally important issue of AF search algorithm performance assessment.

TNI denoted the number of iterations required for a search algorithm to converge and move to the estimated in-focus position. This metric can be viewed as a system independent measure of AF search speed. If the AF search algorithm implementation can analyze the sharpness information, decide the next focus actuator movement amount, and move the actuator by the decided movement amount within the blanking interval between two consecutive frames, then the total physical AF time in seconds could be simply computed as the TNI multiplied by the sensor frame rate. In some systems, more frames may be consumed than the TNI due to many factors such as the need to skip corrupted frame data or there not being enough time between consecutive frames for the actuator to move the focus to the desired next position. In either case, TNI can provide a rough indication of the AF speed performance from a purely algorithmic convergence speed point of view. With this in mind, AF search algorithm speed performance can be evaluated in an offline simulation environment to determine which algorithm converges the fastest over a set of real-world focus sequence data.

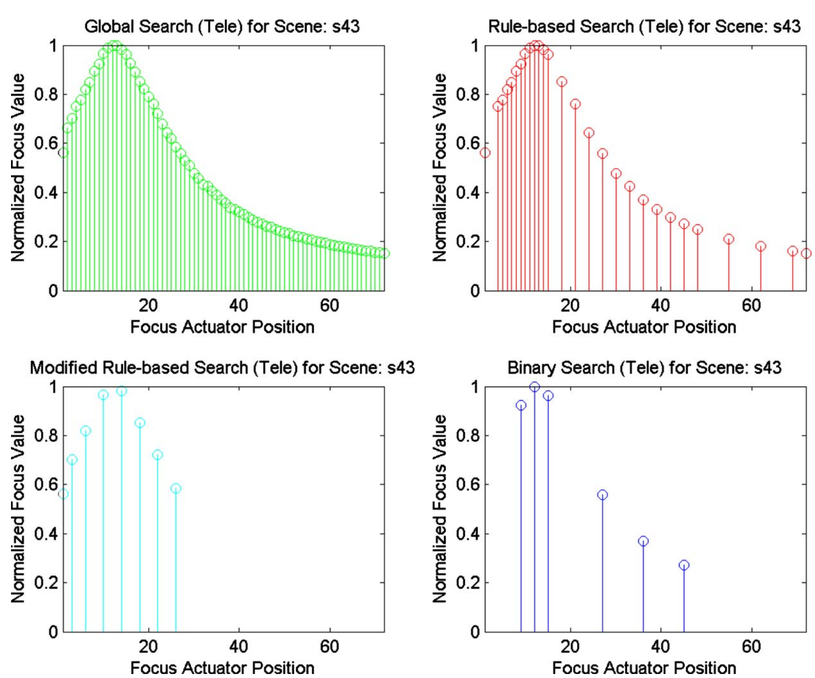

Figure 4. AF search algorithm differences between Global search (GS), Rule-based search (RS), Modified rule-based search (MRS), and Binary search (BS).

Figure 5. Texas Instruments Digital Camera Development System with 3 MPix camera module.

TDM provides the number of focus actuator steps traversed during the entire search process from start to end. This metric can be regarded as a measure of power consumption, noting that more power is consumed by the focus actuator when moving the lenses over larger distances.

OFT refers to the residual error of a search algorithm in bringing the object of interest into focus, which is defined as the absolute difference between the estimated in-focus position and the GS-found or true in-focus position. Thus, it is a measure of AF search accuracy. The offset is characterized in terms of the maximum allowable offset or tolerance of a certain number of focus actuator steps defined in turn by one-half the depth-of-focus. For a camera system, the depth-of-focus can be defined as the lens f-number multiplied by the maximum tolerable blur circle diameter. If the offset is less than the maximum offset, the AF search is considered accurate for all practical purposes.

IPO denotes the number of focus actuator positions by which a search algorithm passes the true in-focus position before realizing the peak was passed and then returning to the estimated in-focus position. This is one measure of user discomfort or user experience for a passive AF system, as consumers tend to complain if the passive AF search passes the peak by a noticeable amount before going back to the estimated in-focus position. This metric has not been adequately used to judge the performance of a search algorithm in the past, but should be taken into consideration, especially in a consumer camera design.

TNDC denotes the number of direction changes a search algorithm goes through to determine the final estimated in-focus position. This is another measure of user experience, as it is not ideal for a search to rapidly oscillate around the in-focus position before determining the estimated position since it provides a huge discomfort to the user to see the object come in and out of focus multiple times before arriving to the final estimated in-focus position. In practice, due to hysteresis effects of the focus actuator movement, it is beneficial that the in-focus position be approached consistently from the same direction. An AF search algorithm with a lower TNDC is therefore a more appropriate choice for a consumer camera system.

OVERVIEW OF SEARCH ALGORITHMS

Selecting a State-of-the-Art Set for Performance Evaluation

In order to judge the value in the simultaneous use of the five proposed AF performance metrics in assessing the performance of an AF search algorithm, it is necessary to select a set of such search algorithms for evaluation purposes. An overview of known AF search algorithms presented in the open literature is provided and a set of state-of-the-art representative search algorithms is then selected for further real-world performance analysis.

As far as AF search algorithms are concerned, several attempts have been made to determine the in-focus position quickly without overshooting or oscillating around the peak as consumers desire a smooth AF experience with minimum overshoot and no rapid oscillation between extreme levels of focus and defocus.[5,6] The efficiency of the search depends on the number of times the distance between the lens and image sensor is adjusted to bring the image into focus. From a purely algorithmic point of view, the main objective in the development of any passive AF search algorithm is to reduce the number of iterations and thus to lower the autofocusing time while not compromising sharpness quality or accuracy.

Many different types of search approaches can be found in the open literature including Global Search, Iterative Coarse-to-Fine Search, Divide-and-Conquer Search, Prediction Search, and Variable Step-Size Sequential Search. The Global Search (GS) approach sequentially searches every position in the search space, and uses the position of maximum sharpness as the in-focus position. A GS-found in-focus position provides the true in-focus position and thus can be used to compare the accuracy of other search methods.

Iterative coarse-to-fine approaches include Choi's fast hopping search,[8] which combines a coarse scan with GS near the estimated peak location, and Li's fixed step-size coarse search,[9] which uses a fine scan near the estimated coarse peak. The divide-and-conquer approach is exemplified with the Fibbonaci search[10] or a Binary search. Although this search is optimal in minimizing the number of iterations for a given search space, it is not a viable method for a consumer camera AF system due to the rapid oscillation around the peak and its inefficiency in total distance moved.[5,6] Chen et al. presented a prediction search to forecast the turning point of the sharpness measure which helped to reduce the number of iterations.[4] Several variable step-size search methods have been proposed for adjusting the speed of search, the key differentiator in such methods lies in how to determine the focus actuator step-size between subsequent search iterations. Fuzzy rule-based[11,12] and crisp rule-based[3,13] methods have been applied to adjust the step-size in a heuristic manner, while others have adapted the step-size in order to keep the gradient of the sharpness measure constant.[14] Yao et al. used a Maximum-Likelihood statistical approach to determine thresholds in a crisp rule-based type search for the adjustment of the step-size.[15]

Yao et al. also presented a study of sharpness measures and search algorithms,[16] where it was found that our previ-

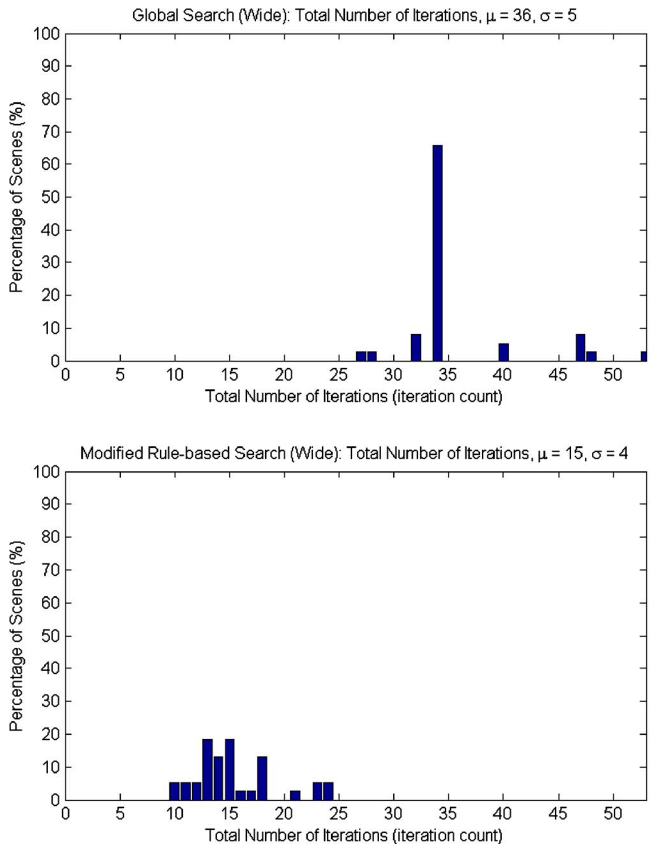

Figure 6. Comparison of AF search TNI histograms in Wide zoom for GS, RS, MRS, and BS.

ously introduced variable step-size Rule-based Search (RS)[13] outperformed other search algorithms in terms of accuracy and convergence speed. In other words, it has been independently verified that such a sequential search is able to reduce the number of iterations and to eliminate the oscillation found in the divide-and-conquer approaches. In addition to the Yao evaluation, the effectiveness of the RS approach was also confirmed along with the addition of several improvements to it, named Modified-RS (MRS), which ultimately achieved better performance than the original RS.[14,17]

It is worth mentioning here that while the Binary search (BS) seems to require fewer numbers of iterations and total distance moved, it has the highest number of direction changes, which can cause positioning difficulties due to hysteresis effects commonly experienced in most existing focus actuator technologies available today.[13] Thus, in practice, the AF time for BS would be much longer than RS or MRS methods which only require one direction change to get back to the found in-focus position after passing over the peak by a few focus actuator positions. It should also be noted that as the number of direction changes increases, positioning reliability of BS decreases due to hysteresis.

From this discussion, we have selected the following four search algorithms for further evaluation: Global search (GS), Rule-based search (RS), Modified Rule-based search (MRS), and Binary search (BS). Figure 4 shows an example of the GS, RS, MRS, and BS searches. This figure depicts the difference in step sizes between the search algorithms for real sharpness function data taken with the optical zoom set to tele-angle. From this figure, it can be seen that it is not necessary for RS,[13] MRS,[17] and BS[13] to search through every focus actuator position to determine the in-focus position, as needed in the GS approach. The RS and MRS approaches, make use of the percentage difference between two consecutive sharpness values in order to adapt the step size to the shape of the sharpness function curve. In the RS approach, when the search encounters a significant rise in the sharpness value, it switches over to a smaller step-size increment and after having passed the peak, the search then continues with a larger increment. For the MRS approach, the fine step-size increment is eliminated to save on iterations and a peak-detection module is used to stop the search after passing a sampled peak sharpness value by a certain percentage over consecutive search iterations. The BS approach uses a divide-and-conquer mechanism to determine the peak location. As the emphasis of this article is on the AF search performance evaluation using the proposed metrics, the interested reader is referred to the respective papers for more detailed information on the AF search algorithms.

EXPERIMENTAL RESULTS

The AF performance of the above four representative AF search algorithms was assessed using the five proposed metrics. A focus sequence data set consisting of 88 different scenes taken of objects of various texture and contrast at various scene illuminations and distances, both in Wide and

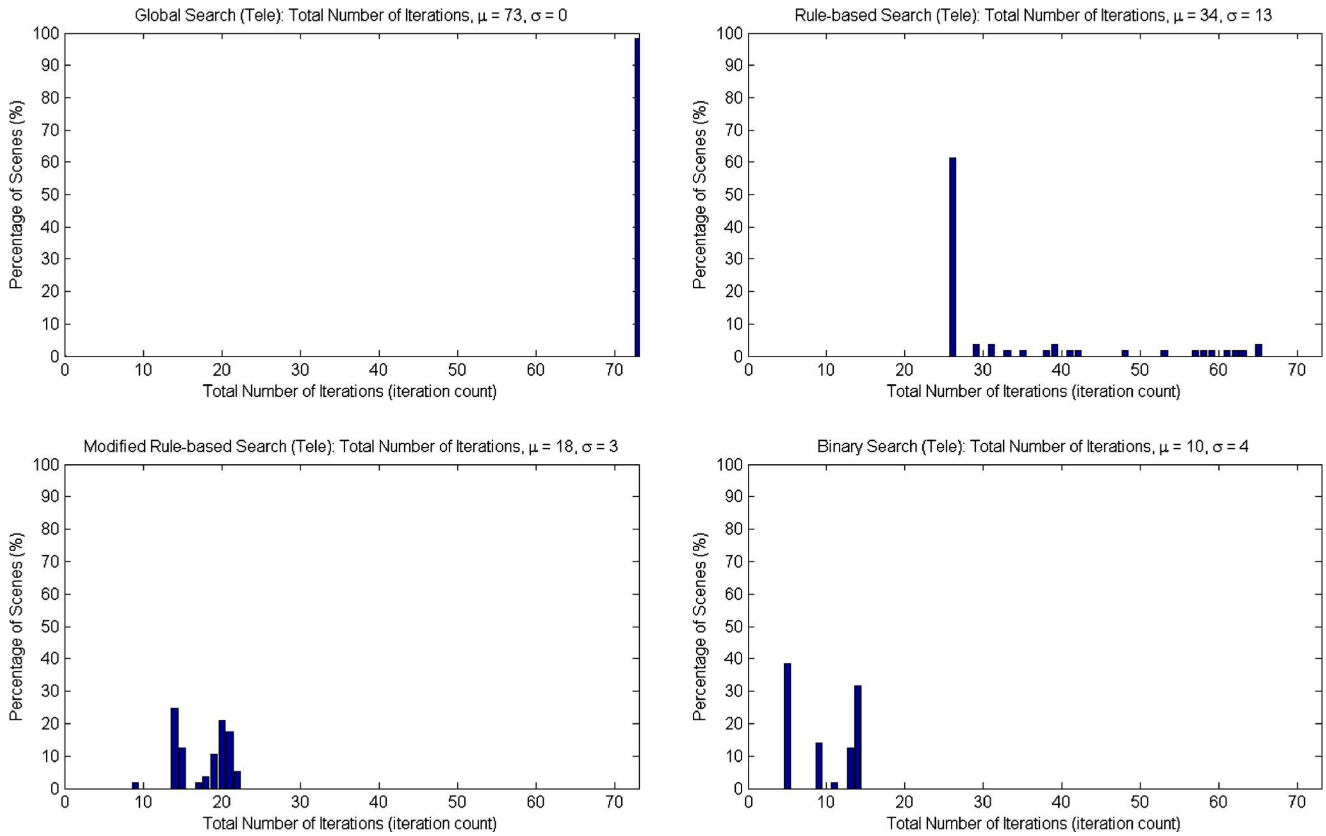

Figure 7. Comparison of AF search TNI histograms in Tele zoom for GS, RS, MRS, and BS.

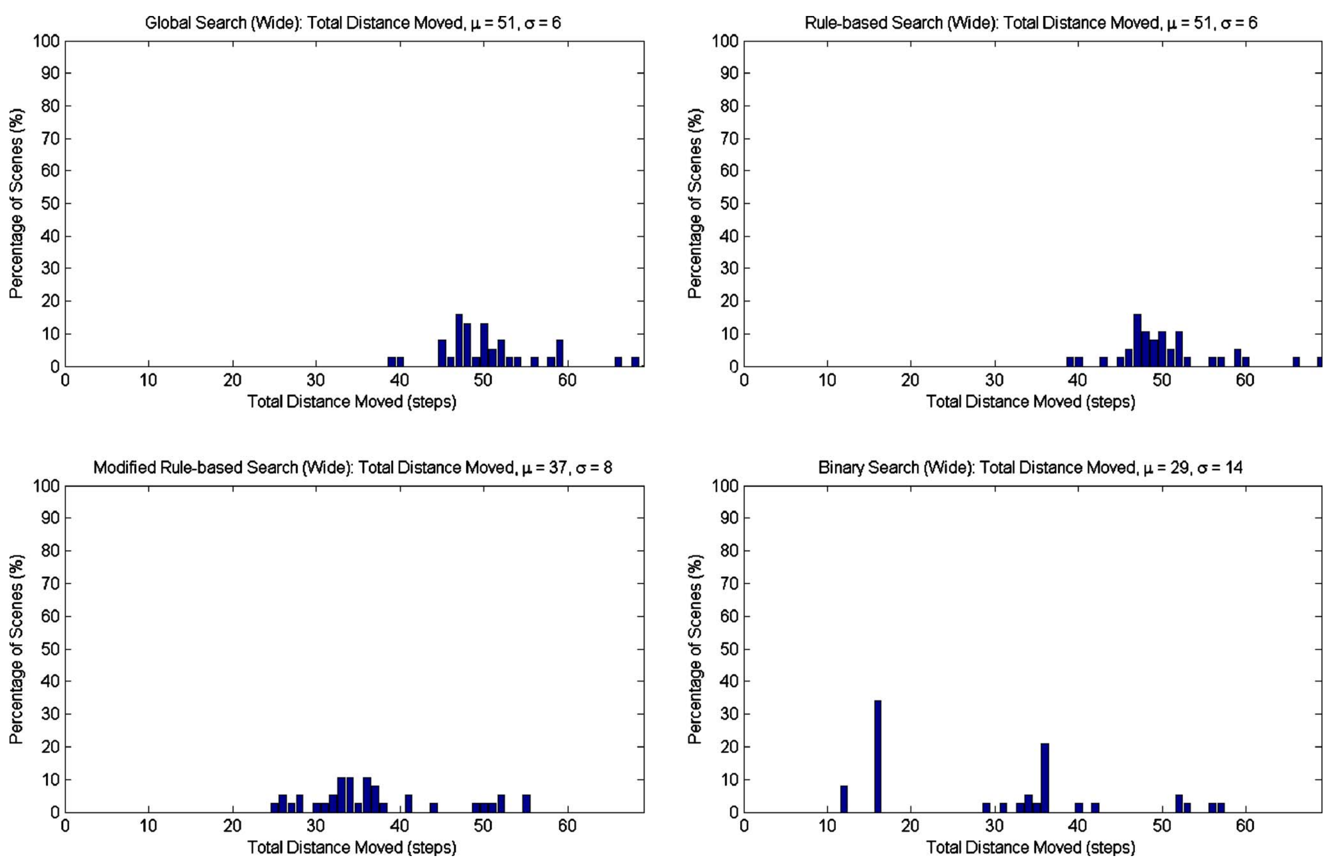

Figure 8. Comparison of AF search TDM histograms in Wide zoom for GS, RS, MRS, and BS.

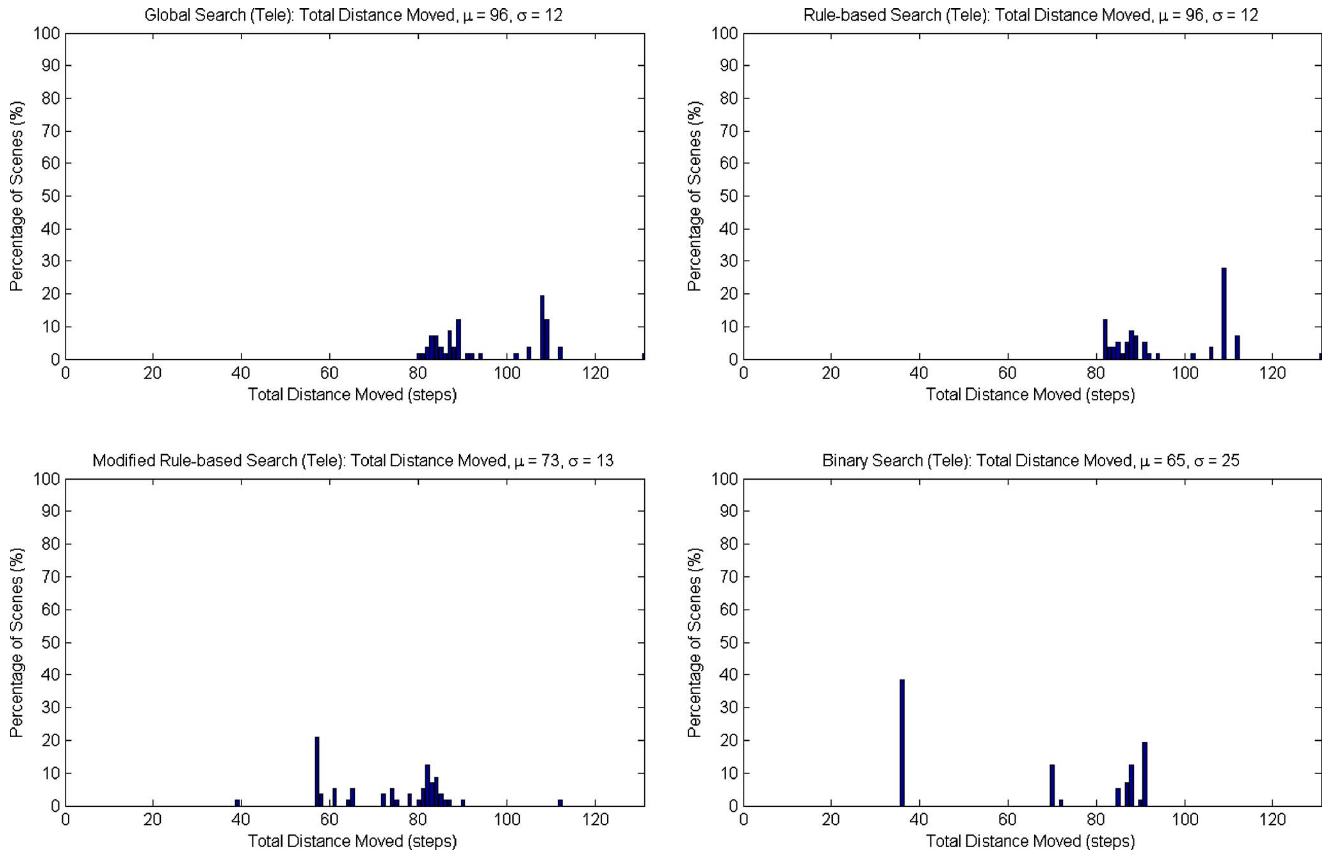

Figure 9. Comparison of AF search TDM histograms in Tele zoom for GS, RS, MRS, and BS.

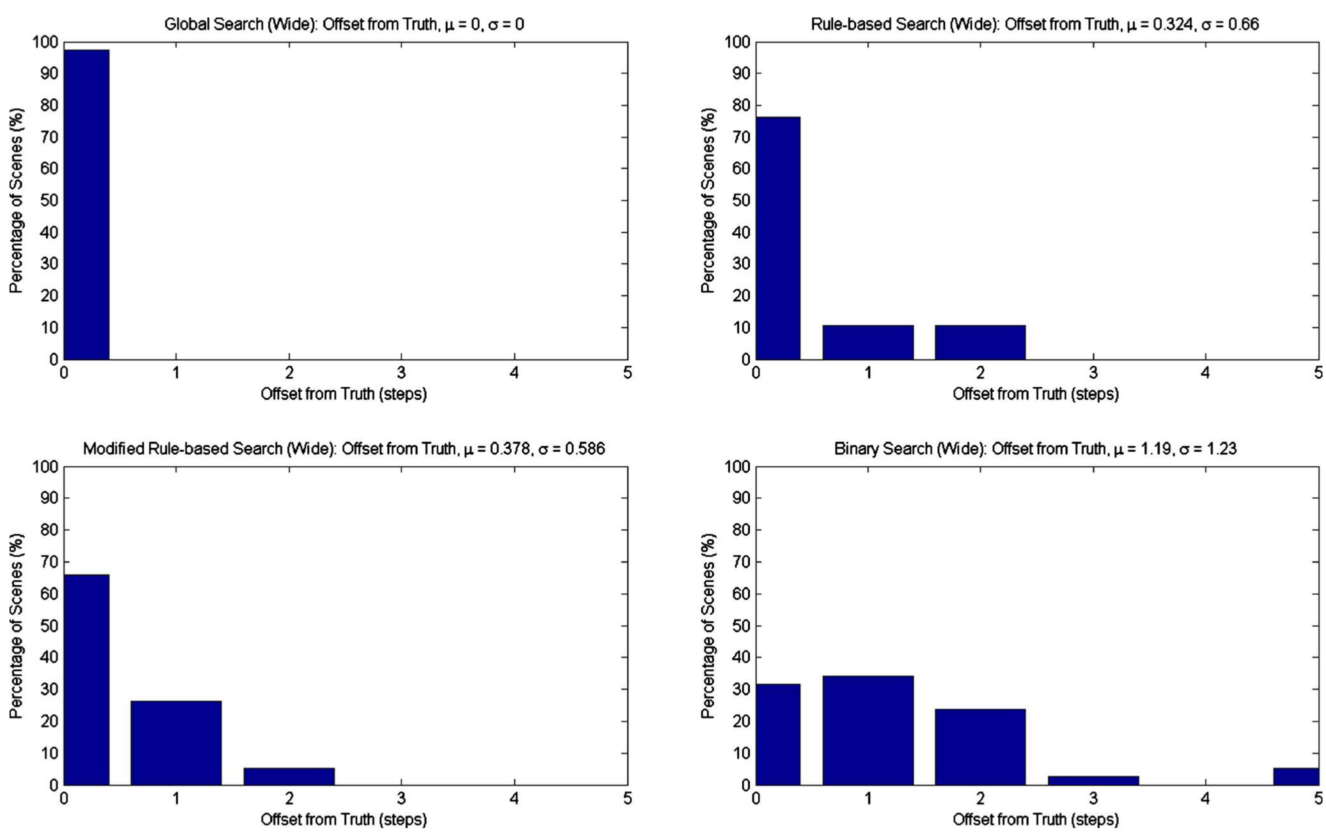

Figure 10. Comparison of AF search OFT histograms in Wide zoom for GS, RS, MRS, and BS (tolerance =4 steps offset).

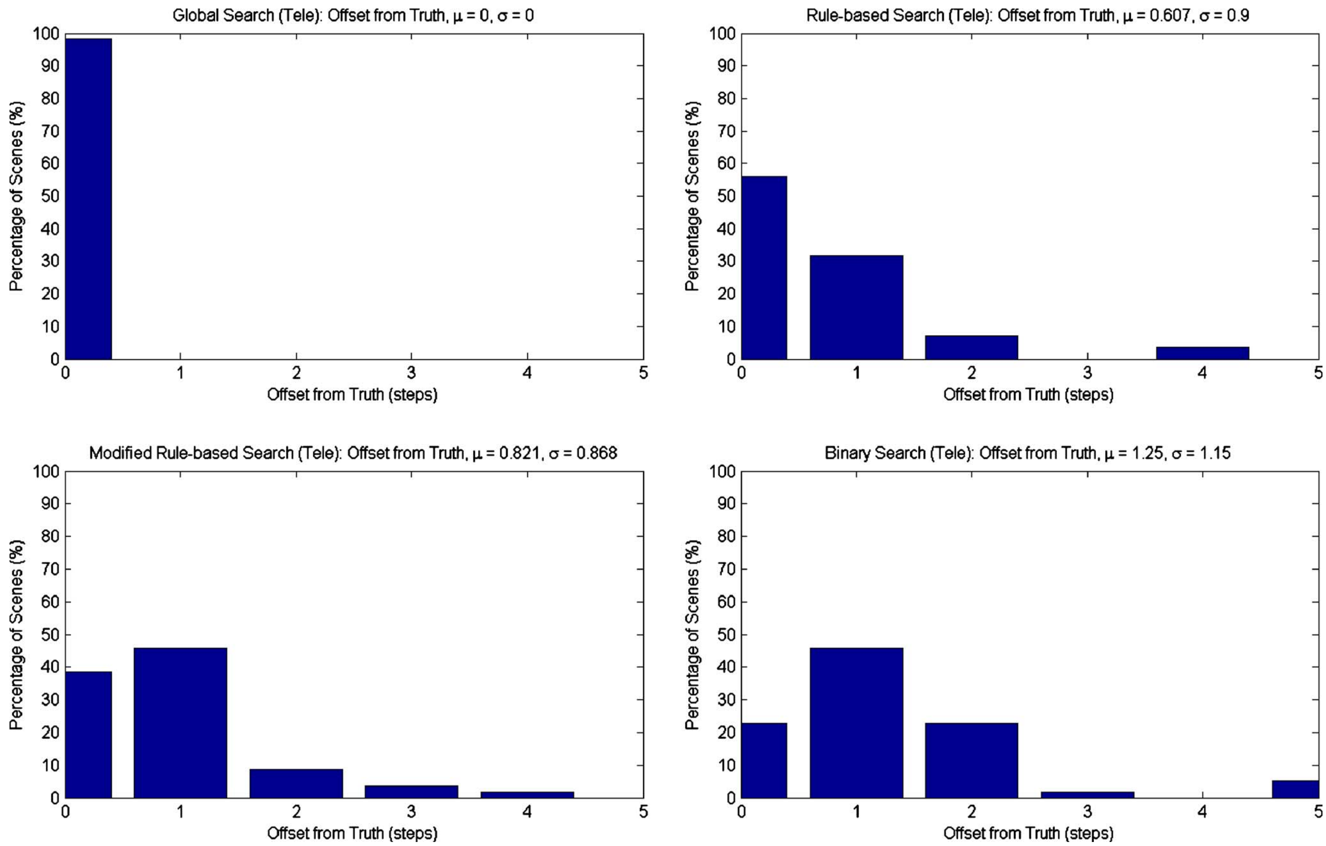

Figure 11. Comparison of AF search OFT histograms in Tele zoom for GS, RS, MRS, and BS (tolerance=4 steps offset).

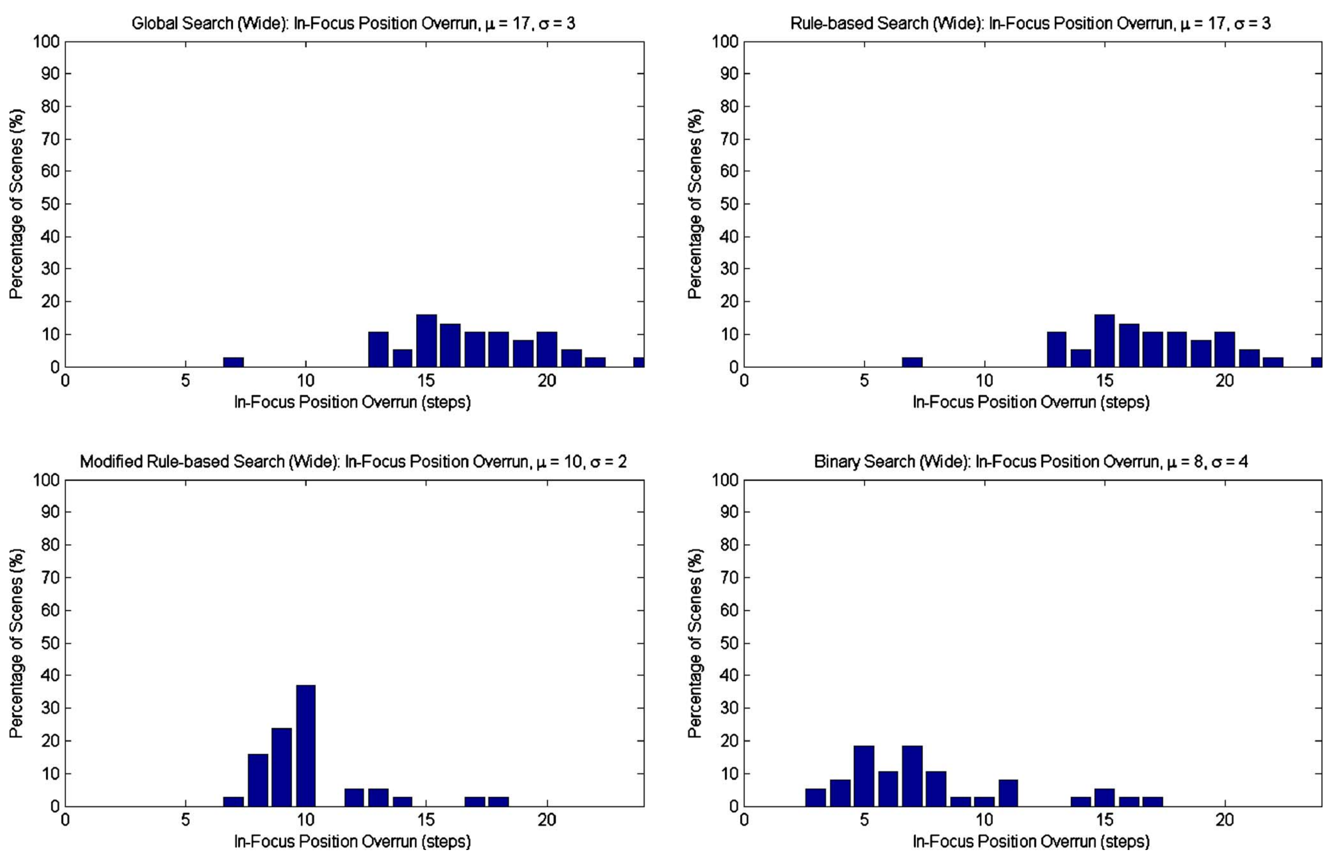

Figure 12. Comparison of AF search IPO histograms in Wide zoom for GS, RS, MRS, and BS.

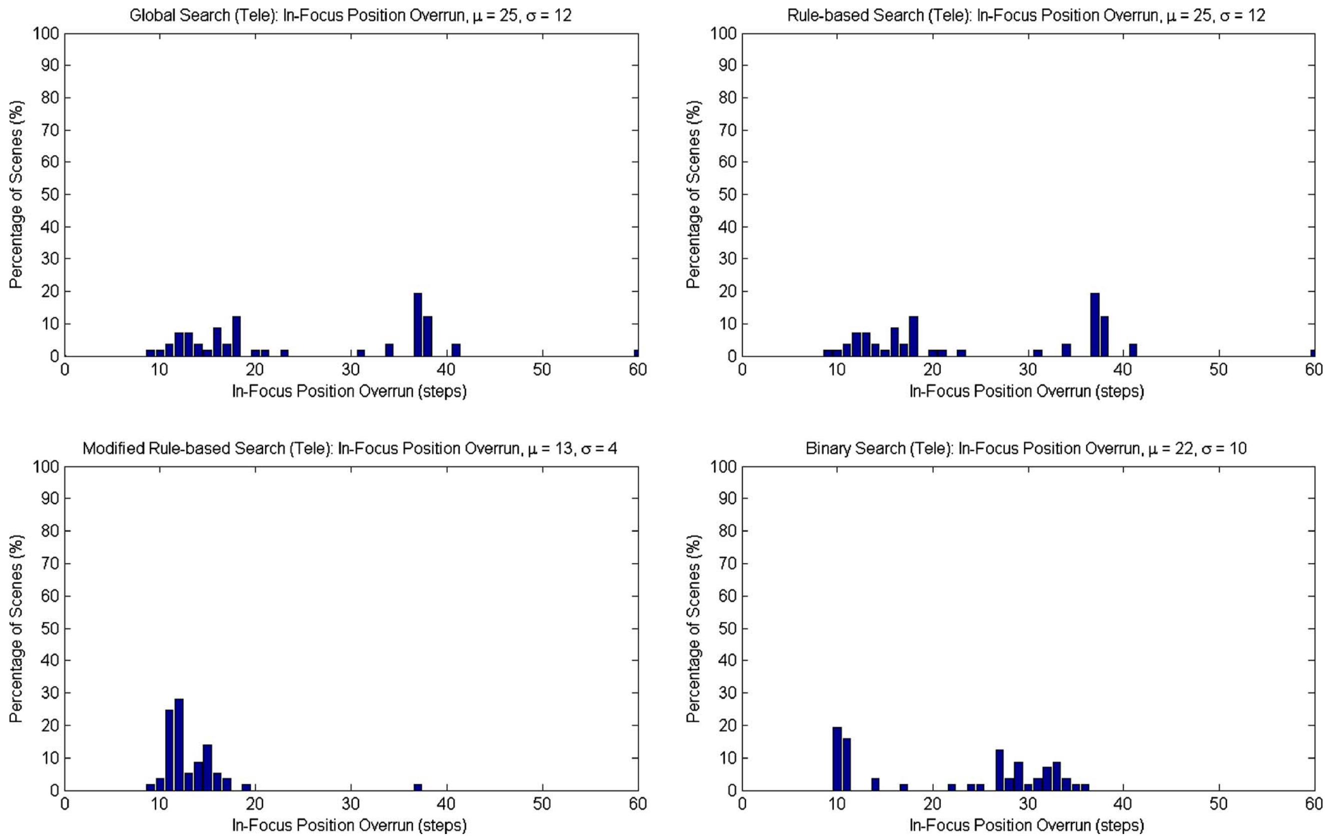

Figure 13. Comparison of AF search IPO histograms in Tele zoom for GS, RS, MRS, and BS.

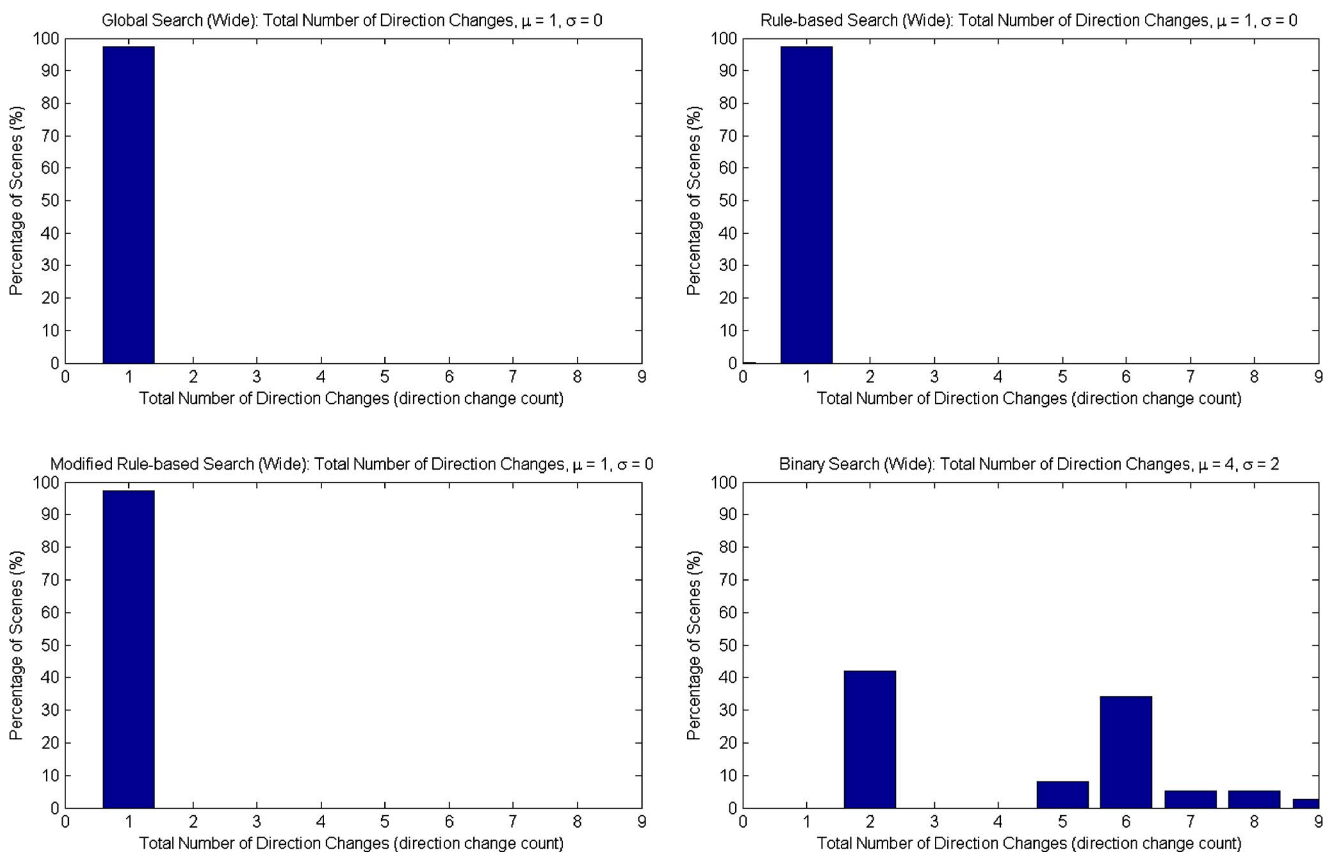

Figure 14. Comparison of AF search TNDC histograms in Wide zoom for GS, RS, MRS, and BS.

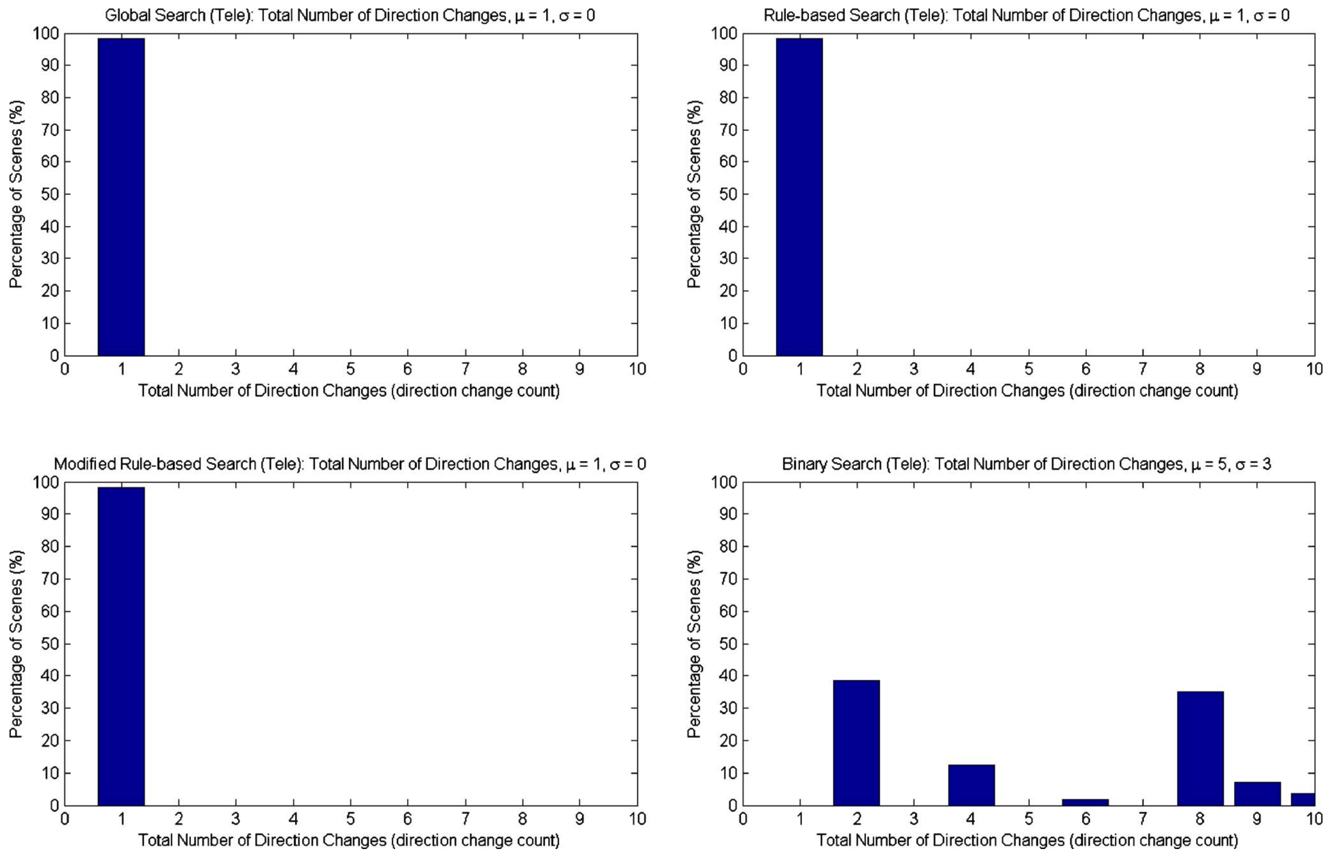

Figure 15. Comparison of AF search TNDC histograms in Wide zoom for GS, RS, MRS, and BS.

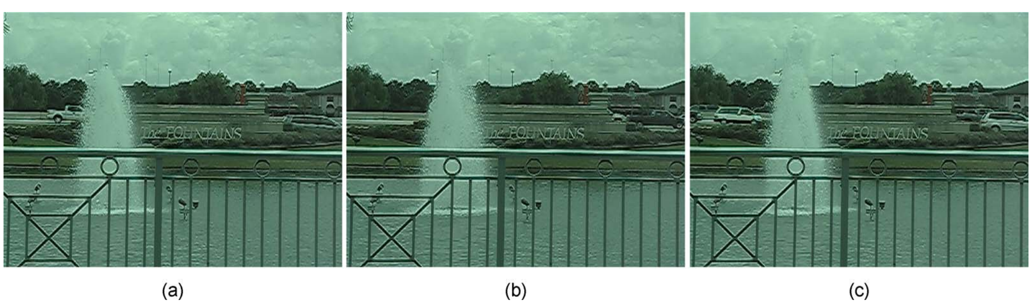

Figure 16. OFT comparison for (a) GS w/0 steps offset, (b) RS and MRS w/2 steps offset, (c) BS w/5 steps offset for scene number 78 (Tele).

Tele zoom, was captured using a prototype digital camera development platform known as the Texas Instruments Digital Camera Development System (DDS) shown in Figure 5. This camera system consisted of a 3 megapixel CCD image sensor with a 3× optical zoom lens system and a stepper-type focus actuator. The camera processor was the Texas Instruments TMS320DM320 digital camera processor. The Wide zoom had a focal length of 6.39 mm and an f-number of 2.9, while the Tele zoom had a focal length of 18.04 mm and an f-number of 3. The pixel pitch of the image sensor was 2.575 μm.

Raw, draft preview, Bayer-pattern focus sequences, which are sequences consisting of Bayer-pattern images taken at each focus actuator position in the search domain,

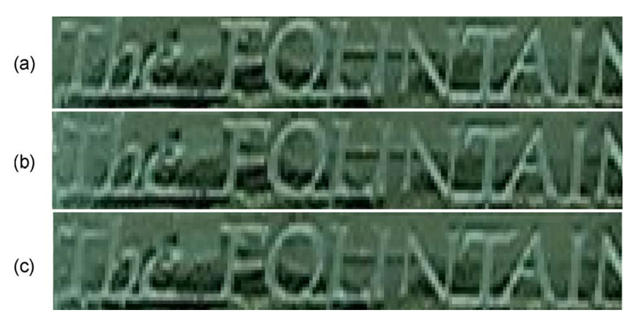

Figure 17. Zoomed in view OFT comparison for (a) GS w/0 steps offset, (b) RS and MRS w/2 steps offset, (c) BS w/5 steps offset for scene number 78 (Tele).

Figure 18. IPO comparison for (a) GS found in-focus position, (b) MRS w/IPO=9 steps, (c) BS w/11 steps offset, and (d) GS and RS w/IPO=24 steps for scene number 52 (Wide).

were collected for each scene. The camera system software was configured to run a Global search and dump the Raw data from off the image sensor at each focus actuator position from SDRAM to an SD card. For the CCD image sensor of the prototype camera, draft preview data was output with image resolution of 2080(horizontal)$\times$256(vertical) with a bit-depth of 14-bits per pixel and a start-pixel color of green. The database of RAW data and sample converted JPEGS (resized to 640×480 for easier viewing) are made available for use by the research community on the internet.[18] These focus sequences were preprocessed with a noise reduction preprocessing filter[19] and then further processed using the squared gradient focus measure.[3] The focus measure was accumulated in each individual zone of a 3×3 focus grid covering the entire frame.[3] The focus measure from the central zone was used for evaluation in the majority of scenes, although some scenes used a manually selected zone, depending on the object of interest. The database contains an Excel spreadsheet with details on what zone was used for the different scenes.

The performance of the four search algorithms on the collected focus sequence database was analyzed using the proposed five metrics. To get a better sense of the statistical nature of the search algorithm performance over the entire database of scenes, the results are provided as histograms of the five metrics, presented separately for both Wide and Tele, in Figures 6–15 (with mean and standard deviation explicitly denoted in the subtitles).

The entire set of five AF search performance metrics provides a comprehensive view of the performance of the individual search algorithms. For evaluation, the search algorithms can be ranked in terms of the results presented. For TNI, BS outperforms the other algorithms and from this data alone, it seems that it would provide the fastest convergence to an in-focus position. For full analysis, the TNDC should be taken into account in which BS performs the worst. While BS may have the lowest TNI in simulation, due to the number of direction changes combined with hysteresis effects of the focus actuator which are encountered in practice, BS is not a recommended search algorithm. If AF search algorithm performance only considered accuracy and speed, one might incorrectly come to the conclusion that BS would be the optimum choice, but it is the simultaneous analysis of TNI and TNDC which can help to realize BS might not be the best choice. With the superiority of BS eliminated, it can be seen that MRS consistently outperformed the other search algorithms by having lower total number of iterations (TNI), total distance moved (TDM), and position overrun (IPO) with accuracies (OFT) within the tolerance limits. The offset values should be compared to the maximum tolerable or allowable offset as noted in the parenthetical note in Figs. 10 and 11. Any AF search algorithm which produces an offset lower than the maximum tolerable offset produces a visually sharp image. The maximum OFT for BS exceeded the maximum tolerable offset, although this was for a low percentage of the scenes. The other algorithms remained within the accuracy limits. Figures 16 and 17 illustrate the OFT for the search algorithms. Fig. 16 provides an overview of the scene, while Fig. 17 zooms in on the central portion. The effects of the five-step offset of BS can be seen in the text portion.

Another interesting comparison from an image quality point of view is the IPO metric. A comparison of the IPO can be seen in Figure 18. In this case, GS and RS are the worst performers, since they pass the in-focus position by a greater amount than MRS and BS. The closer the search can stop near to the true in-focus position the faster the convergence, and it gives a good impression to the user since the search does not impart too much blur to the scene after coming into focus.

It is worth mentioning that the emphasis of this article has not been on the selection of a passive AF search algorithm, but rather to provide a framework for evaluating the performance of any passive AF search algorithm which is afforded by simultaneous analysis of the proposed five AF search performance metrics. In this article, GS, RS, MRS, and BS have been selected as four representative state-of-the-art search algorithms to illustrate how the performance comparison could be done for any new search algorithm that a camera manufacturer or designer may wish to use. The proposed metrics can be used to characterize the real-time performance of the algorithms in real-world situations via use of focus sequence databases which could be collected with any prototype camera development system. In essence, when evaluating a passive AF system, it is suggested that all aspects of speed, accuracy, power consumption, and user experience are taken into consideration at the same time by use of the proposed five AF search algorithm performance metrics.

CONCLUSIONS

This article has examined the issue of how to assess the performance of any type of passive AF system, in particular its underlying search algorithm. A comprehensive set of five metrics including the total number of iterations (speed), offset from truth (accuracy), total distance moved (power consumption), in-focus position overrun (user experience), and total number of direction changes (user experience) has been proposed. Experimental results comparing the performance of four representative AF search algorithms using a real-world database of Raw focus sequences using a prototype digital camera were presented to show how to carry out the evaluation of any passive AF search algorithm.

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