Noise Sensitivity Analysis for Shape from Focus Methods

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Shape from focus (SFF) methods provide a useful technique for passive autofocusing and three-dimensional (3D) shape recovery of objects. In these methods, focus measures are used to extract 3D information from a sequence of images taken with different camera parameters such as lens/object position or focal length. The accuracy of autofocusing and 3D shape measurement using the image focus analysis technique depends on the particular focus measure that is used.

Experimental evaluations of different focus measures have been reported by some researchers. In the existing literature, all known work have been a combination of experimental observations and subjective judgement. The noise sensitivity of a focus measure depends not only on the noise characteristics but also on the image itself. The optimally accurate focus measure for a given noise characteristics may change from one object to the other depending on its image. This makes it difficult to arrive at general conclusions from experiments alone.

For a given camera and object, the most accurate focus measure can be selected from a given set through experiments by many trials. The focus measure with the minimum estimate of root-mean-square (RMS) errors is taken to be the optimal. In practical applications such as consumer video cameras or digital still cameras, it is desirable to find the best focus measure from a given set by autofocusing only once. It is quite undesirable to repeat several trials.

If one has a detailed and accurate information on the focused image of the object to be focused and the camera characteristics such as its OTF, noise behaviour, and camera parameters, then it would be possible to estimate the RMS error theoretically with only one trial. However such information is rarely available in practical applications.

In the absence of such detailed and accurate information, I address this important problem and derive theoretical results and provide supporting experimental results. The theroy based on probability and stochastic processes is able to give the computation of RMS error with only one trial of autofocusing. It is assumed that each focus measure γ at lens position s_i is associated with a probability density function $P_i(\gamma_{s_i})$, and the focused position s_k is with the maximum focus measure which has the highest probability as compare to all the value of the focus measure computed at every lens position. Therefore, we obtain

$$\begin{aligned} & \tilde{P}(s_k = focus\ position) \\ = \; & P_0(\gamma_{s_k} > \gamma_{s_0})P_1(\gamma_{s_k} > \gamma_{s_1}) \cdots P_n(\gamma_{s_k} > \gamma_{s_n}) \\ = \; & \prod_{s_i = s_0, s_i \neq s_k}^{s_n} P_i(\gamma_{s_k} > \gamma_{s_i}) \end{aligned}$$

As the density function $P_i(\gamma_{s_i})$ is known, the equation of RMS error can be derived. In the experiments, the density function is assumed as a normal distribution for the most cases. A rigorous and general noise sensitivity analysis for a large class of focus measures is also derived. The assumption is made weakly based on only an additive noise with homogeneous zero mean. There is no any fitting function involved. In SFF applications, RMS errors in lens position can both be easily translated into uncertainties in depth using the lens formula. The analysis here shows that the autofocusing noise sensitivity of a focus measure depends on the image of the object to be autofocused in addition to the camera characteristics, and is helpful in selecting the best focus measure for a given set of images and noise characteristics.

For an object with unknown focused image, finding the optimally accurate focus measure involves computing all the candidate focus measures at a set of lens positions and computing RMS error for each of the lens positions. Then the lens is moved to around the focused position estimated by the optimal focus measure (which has minimum RMS error). Usually the number of candidate focus measures that should be considered for good performance is only a few. Also, almost all focus measures require only a modest amount of computing. Therefore selecting the optimal focus measure from a candidate set comes at a small computational cost.

The results of computer simulation experiments for different signal-to-noise ratios under the assumption of zero-mean Gaussian noise have shown in a good agreement with the theroy. Experiments on actual camera systems are being undertaken to further support the theoretical results.

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