J. Vis. Commun. Image R. 36 (2016) 122–129

Contents lists available at ScienceDirect

J. Vis. Commun. Image R.

journal homepage: www.elsevier.com/locate/jvci

A model-based approach to camera's auto exposure control ☆

Yuanhang Su [a,*], Joe Yuchieh Lin [b], C.-C. Jay Kuo [b]

[a] Shanghai Aerospace Electronic Technology Institute, 1777 Zhongchun Road, Minhang District, Shanghai, China
[b] University of Southern California, Ming Hsieh Department of Electrical Engineering, 3740 McClintock Avenue, Los Angeles, CA, United States

ARTICLE INFO

Article history:
Received 14 June 2015
Accepted 19 January 2016
Available online 25 January 2016

Keywords:
Auto exposure control
Convex function
Digital cameras
Numerical analysis
Control systems
Robust systems
Fast convergence
Secant method
CMOS digital cameras
HDR

ABSTRACT

A fast and robust camera's auto exposure (AE) technique is proposed in this work. It is achieved by modeling the luminance characteristics of the imaging sensor as a concave or convex function of a control parameter (*e.g.*, exposure time or speed) and the optimal control parameter is computed using a modified secant algorithm with fast convergence. Furthermore, the proposed solution is able to adjust the control parameter automatically in the presence of erroneous exposure. Its superior performance is confirmed by experimental results.

1. Introduction

Auto exposure (AE) control is an important function in modern digital cameras. It enables a camera to automatically adjust its exposure settings to adapt to the scene for the imaging purpose. Despite the recent development of the high dynamic range (HDR) imaging system in the high end digital camera market, AE is still widely used in today's digital cameras. This is especially true for video cameras and medium to low end cameras in smart phones and laptops. Furthermore, AE is one of the required modules in existing HDR imaging systems. Although the AE problem and its implementation have been well studied, there are still a few challenges to address.

One of the challenges is to develop a general AE solution that covers a wide variety of imaging sensors. Different sensors use different AE control methods, where each method has its own specific control parameters. Specifically, camera aperture control, automatic gain control (AGC) and electrical shutter control are three main methods [1]. Camera aperture control adjusts the amount of light intensity or irradiance to pass onto the sensor. AGC adjusts the analog or digital gain of input signals. Electrical shutter control adjusts the exposure time for the complementary-oxide-semiconductor (CMOS) imaging sensor or the shutter speed for the charge-coupled-device (CCD) imaging sensor.

An assumption of a linear relationship between the exposure time and the image brightness level (BL), which is the averaged brightness value per pixel, was made in Kuno and Sugiura [2] and Liang et al. [3]. However, the limited dynamic range of imaging sensors contributes to the non-linear characteristics due to over- or under-exposure as shown in Fig. 1, where a simplified relationship between the image BL and the control parameter of an imaging sensor is illustrated. It can be seen that the so called linear relationship is actually piece-wise linear. Details of this non-linearity will be further discussed in Section 3.4.

The AE control in CCD cameras is achieved by selecting a proper shutter speed, which has a reciprocal relationship with BL. A root-finding technique, called the false position method, was adopted by Cho et al. [1] to determine the shutter speed for desired AE performance. The AE control in CMOS cameras, which are most common in today's consumer electronics, is determined by the exposure time. An iterative method to search for the proper exposure time was proposed by Liang et al. [3]. Although these two methods work well in a normal lighting condition that satisfies their respective specifications, they do encounter a tumbling effect under a dim lighting condition. This problem is still not well resolved today. Such a constraint limits the AE control performance

☆ This paper has been recommended for acceptance by M.T. Sun.

* Corresponding author at: 5-A-201 Changxing Hao Rizi, Xinbei District, Changzhou, Jiangsu, China.

E-mail address: suyuanhang@hotmail.com (Y. Su).

http://dx.doi.org/10.1016/j.jvcir.2016.01.011
1047-3203/

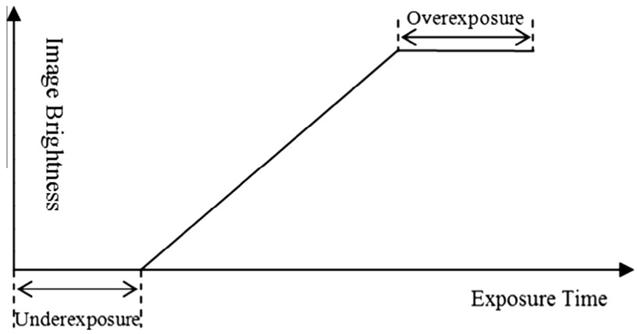

Fig. 1. Simplified relationship between image brightness and exposure time of an imaging sensor.

for imaging sensors. The cause of the tumbling effect and its solution will be elaborated in Section 3.

To implement AE control in a resource constrained environment such as phone cameras presents another challenge. Some advanced techniques developed to tackle high contrast lighting conditions are computationally intensive, and they are not as competitive as the HDR camera [4,5] in the high end market. The histogram of image brightness or other statistical approaches are used [6–10] to detect whether the region of interest is over-/under-exposed and whether the dynamic range of a camera system should be extended. Object detection and image segmentation techniques are used [3,10–12] to determine proper exposure settings. Despite these recent developments, none of them provide robust performance when erroneous exposure occurs.

To address the aforementioned challenges, a fast and robust AE control algorithm was recently developed in Su and Kuo [13] with several attractive features. First, it covers a wide variety of camera sensors yet allows fast and simple implementation. Second, it adjusts itself automatically when erroneous exposure happens. The proposed AE control algorithm is based on convex or concave modeling of the relationship between a luminance function and its control parameter. It determines the control parameter at a predefined BL value using a modified secant method. The proposed algorithm can also be integrated into the HDR camera system as a multiple exposure function [4,5,11].

As compared with prior work [13], the material in Sections 3 and 4 is new. In this work, the convex or concave luminance model is generalized into four categories. The properties of monotonic convergence and error tolerance of the AE control method are proved mathematically. The performance of classic AE control methods can also be well explained. The current work has more thorough mathematical treatment in Section 3 and more extensive experimental results in Section 4.

The rest of this paper is organized as follows. The mathematical background is reviewed in Section 2. The AE function of an imaging sensor is treated as a root finding problem with respect to a convex or concave function in Section 3 and the merits of the proposed AE control algorithm are proved. Experimental results are shown in Section 4. Finally, concluding remarks are given in Section 5.

2. Background review

Root-finding algorithms have been developed in numerical analysis to solve $f(X) = 0$ for variable X without the exact form of $f(\cdot)$. In practice, this can be generalized to the solution of $f(X) - F_t = 0$, where $F_t = f(X_t)$ is the target function value and X_t is the final solution. Several root-finding algorithms are reviewed and their limitations are explained below.

2.1. Bisection method

Given two arbitrary initial points x_0 and x_1 of opposite signs, the bisection method calculates new point x_{n+1} recursively as

$$X_{n+1} = \frac{X_n + X_{n-1}}{2}, \quad n = 1, 2, 3\ldots \tag{1}$$

where X_n and X_{n-1} are chosen according to the root bracketing rule such that $f(X_n)$ and $f(X_{n-1})$ are of opposite signs throughout the iteration. This is accomplished by either keeping X_{n-1} unchanged or updating X_{n-1} with the value of X_n depending on the sign of $f(X_{n+1})$. Then, update X_n with the value of X_{n+1}. The above iteration stops if the distance between $f(X_{n+1})$ and F_t (or the distance between X_{n+1} and X_n) is less than a preset threshold. Then, X_{n+1} is chosen as the desired solution.

In the context of AE control, x_0 and x_1 can be chosen as the minimum and maximum of the control parameter, respectively, to ensure that the solution lies in interval $[x_0, x_1]$. One of the advantages of the bisection method is that it always converges so that a solution can always be found if $f(\cdot)$ is continuous.

However, the bisection method is not suitable for AE control since its root bracketing rule does not guarantee monotonic convergence. That is, $f(X_{n+1})$ may alternate its sign under certain cir-

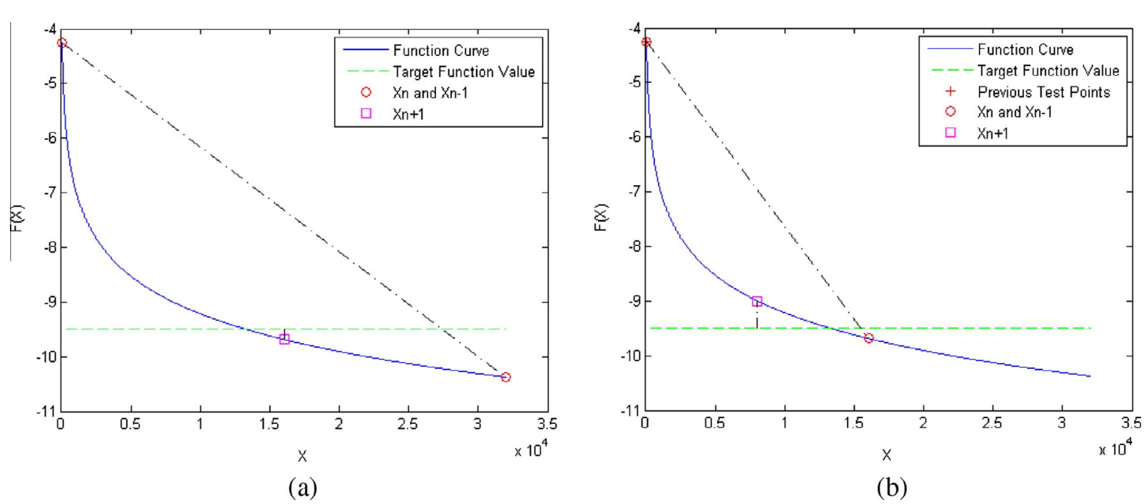

Fig. 2. Illustration of the tumbling effect of the bisection method with $f(x) = -ln(x+20)$, where ln is the natural logarithm. The target value is $F_t = -9.5$ while the initial values are $X_0 = 50$ and $X_1 = 32{,}000$. (a) The first iteration gives $X_2 = 16{,}025, f(X_2) = -10$ which is smaller than F_t. (b) The second iteration gives $X_3 = 8037.5, f(X_3) = -9$ which is larger than F_t.