High Dynamic Range Imaging System for the Visually Impaired

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Abstract. This paper describes a portable High Dynamic Range (HDR) imaging system for visually impaired people, intended to display contrast enhanced images of real world environment. The device is composed of a digital camera and head mounted display (HMD) equipped with high resolution screens. The camera is mounted on the HMD to acquire the ambient scene, the acquired images are processed to generate HDR images through the control of local luminance information. The contrast enhancement method adopted in our system is based on pyramidal image contrast structure representation that relies on the local band-limited contrast definition. The imaging system we propose aims at displaying images that meet the visual capabilities related to contrast sensitivity of people with low vision. It also provides a solution to alleviate discomfort problem expressed by these people when they are facing real-world changing light conditions.

Keywords: High Dynamic Range (HDR) · Contrast enhancement · Assistive devices · Visually impaired · Low vision

1 Introduction

The human vision is a complex process that remains largely misunderstood, despite the great amount of studies that propose to describe and model this system. This complexity comes from the fact that the human vision is based on the eye, known as one of the most complex human organs, and regarded as the most powerful sense to collect comprehensive information on our physical world when comparing with hearing, touch, taste and smell. The eye vision

Electronic supplementary material The online version of this chapter (doi:10.1007/978-3-319-16199-0_44) contains supplementary material, which is available to authorized users. Videos can also be accessed at http://www.springerimages.com/videos/978-3-319-16198-3.

L. Agapito et al. (Eds.): ECCV 2014 Workshops, Part III, LNCS 8927, pp. 632–642, 2015.
DOI: 10.1007/978-3-319-16199-0_44

makes easy the daily living tasks, such as mobility and locomotion, reading, driving, face recognition and object manipulation. Furthermore, human eyes have extremely high visual range that can easily differentiate between very bright and dark regions in the same scene and are able to perceive a granularity with ratio on the order of 10.000.000:1 (though instantaneous sensitivity is within a range not larger than 10^2-10^3) from highlights to shadows and even greater if light sources are visible. However, visual performance is sensitive to luminance changing conditions. Under photopic (i.e daylight) luminance levels, visual functions such as acuity, contrast sensitivity, color discrimination, depth perception and motion detection are likely optimal. On the contrary, under low luminance mesopic/scotopic (i.e nightlight) conditions, performance are considerably reduced [1]. These performances severely degrade for visually impaired people who suffer from vision loss and limitation of visual capability resulting from eye diseases, such as glaucoma [2], macular degeneration [3], retinitis pigmentosa (RP) [4], diabetic retinopathy [5], and some other visual disorders.

Progressive peripheral field loss is the most important symptom of RP. At later stages of the pathology, central vision may also be reduced. But even at the earliest stages, many patients complain of difficulties or discomfort in functioning in bright light [6] and experience night blindness. For this population, the partial or total loss of vision affects the quality of life in the way that accomplishing daily activities can really be challenging. While medical and therapeutic treatments, for visual impairment, are still limited in effect, vision adaptation and rehabilitation techniques may help patients to better cope with their disabilities.

In recent years, electronic systems, namely vision aids, have also been designed for assistive applications for the visually impaired. Augmented reality appears as a promising area. Luo and Peli [7] developed a visual field expander based on an optical see-through Head Mounted Display (HMD). Their system superimposes minified edge images of the ambient scene over the wearers see through natural vision. Providing this supplemental visual information, to patients with severely restricted peripheral field (known as tunnel vision), allowed them to find targets outside their residual field of view. Molton et al. [8] propose an image processing technique using stereo-vision system to discriminate the obstacles relative to the ground. Edge enhancement on natural images is investigated as a mean of providing pertinent information to the user [9]. To the best of our knowledge, these electronic aids do not offer luminosity control in both dark and bright levels. Particularly RP users of the optical see-through devices are even more exposed to high lightening conditions because of edge enhancement, which can be painful for them.

In this work, we propose a portable High Dynamic Range (HDR) imaging system that alleviates discomfort problems faced by visually impaired people due to real world changing illumination conditions, especially toward very high or very low illuminations. The conception of this system is conducted in collaboration with low vision rehabilitation specialists (orthoptists, orientation and mobility specialists) in order to match the needs of the visually impaired. This system consists of an advanced HMD coupled with a digital camera. The camera device is used to acquire images of the ambient scene, these images are processed to generate HDR images so that the effect of light changing conditions of the real scene can be ignored, a tone mapping technique is then applied to obtain images that are visually similar to a real scene by careful mapping to a set of luminances that can be displayed on the HMD screen device. The system intend to display live HDR images of ambient scenes in a way that meets the visual capabilities of visually impaired people.

This paper is organized as follows: in Section 2 we present the HDR image generation technique we apply for our portable imaging system. In Section 3, we detail the overall architecture of our system and its application for the visually impaired, especially for people who have RP and Glaucoma. Finally, the conclusion and possible future works are given in Section 4.

2 High Dynamic Range Generation and Presentation

2.1 HDR Radiance Map

Despite recent advances in camera sensing technology, existing cameras are only capable of sensing limited dynamic range, and are still faraway from recovering the high dynamic range of light intensities within a real world scene. Several hardware and software techniques have been developed in order to capture the entire visual information present in a high dynamic range (HDR) scene[10]. When capturing any scene, digital cameras are unable to store the full dynamic range resulting in low quality images where details are concealed in shadows or washed out by bright lights. This is mainly due to the limited bit depth allocated to encode color information of each single pixel. For a true color image representation, considered to approximate natural color rendition, RGB color channels is encoded in 24-bit (8-bit per channel), which offers only 256 levels of tone. This can result in drastic dynamic range compression of the natural color/intensity and in an increase or decrease of pixel saturation toward respectively brighter or darker zones of the image, to end up with low dynamic range (LDR) image. HDR techniques were proposed to overcome this limitation, and make it possible to construct a radiance map that recovers high dynamic range from images acquired by digital cameras by combining multiple images of the same scene at different exposures. Different HDR synthesis methods exist [11–15]. The main concept of HDR image generation is based on combining multiple and differently exposed LDR images of the same subject matter. At least two LDR images are needed to build the HDR radiance map, one acquired with a short exposure time, the other with a high exposure time, respectively resulting in underexposed and overexposed images. With underexposed image, details from brighter areas of the acquired scene are captured, while for the overexposed image, details within the dark areas are highlighted. Debevec and Malik in [12] proposed a method of recovering high dynamic range radiance maps from photographs. They developed an algorithm based on exploiting the physical property of their imaging system and its response function. Knowing these characteristics is very helpful in correctly fusing pixel data from images taken from different imaging systems (photography camera, video camera, film camera, etc) regarding their different digitization processes. In their paper they elaborate the radiance equation for constructing the radiance map, given by:

$$\ln E_i = g\left(Z_{ij}\right) - \ln \Delta t_j \quad (1)$$

Where E_i is the irradiance value for a pixel i, Z_{ij} denotes the pixel value with i the spatial index over pixels and j the index over exposure times Δt_j and g is a monotonic function derived from the sensor reciprocity equation. E_i and g are recovered using a minimization approach based on a quadratic objective function.

2.2 Tone Mapping

Once calculated, radiance map poses a fundamental problem, that is how to map the large range of intensities found in such image into the limited range supported by conventional display devices (e.g. OLED,LED,LCD). The dynamic range of these various devices is much smaller than the dynamic range commonly found in real-world scenes. Therefore, when it comes to displaying an HDR image on LDR output medium, an image processing technique is applied to reduce the dynamic range, and referred to as tone mapping operator (TMO). After a step of enlarging the dynamic range of combined LDR images to generate HDR images, the principle of TMO goes in reverse direction, and it is a step of mapping the large range of intensities found in an HDR image into a limited intensity levels that meet display devices capabilities. Numerous TMO algorithms have been proposed to generate displayable HDR images [10,16–22]. The key issue in tone mapping is then to compress an image while at the same time preserving some attributes of the image. Different TMO algorithms focus on different attributes with the result that we have a large set of algorithms which aim to preserve contrast, visible detail, brightness or even appearance.

2.3 Contrast Processing

Part of a human's ability to discern information is attributed to its capacity to perceive difference in luminance within a field of vision, Human Visual System (HVS) is mostly sensitive to relative luminance ratios (contrast) rather than absolute luminance, this can explain the fundamental adaptation ability of the HVS to real world light conditions. Contrast detection and contrast discrimination are two of the most thoroughly studied topics in vision perception literature [23,24]. Research on contrast have resulted in several definitions of contrast (e.g. simple contrast, Weber fraction, logarithmic ratio), and response of the HVS to grating stimuli (generally sinusoidal gratings) can be modelled by the contrast sensitivity function (CSF). Typically, the CSF is measured by threshold detection measurements or supra-threshold (above contrast detection threshold) contrast measurements [25]. Both permit to quantitatively evaluate variations of HVS's sensitivity over spatial frequencies. Most of contrast definitions and measurement that have been proposed in the literature were defined and derived on simple visual stimulus and simple patterns under normalized conditions, such as sinusoidal gratings or single patch of light on a uniform background. Peli [26] proposed a new definition for quantifying the contrast, designated by local band-limited contrast, which take into consideration the spatial frequency information of the contrast in images. This definition assigns a contrast value to every point in the image as a function of the spatial frequency band. The contrast is measured based on difference between selected levels of a Gaussian pyramid. Unlike the other definitions, the local band-limited contrast is suitable for complex images. However, the resulting difference of Gaussians leads to a band-pass limited measure of contrast, which tends to introduce halo artifacts at sharp edges when it is modified. Mantiuk et al.[19] developed a framework for contrast enhancement and visually appealing tone mapping demonstrated to be robust to noise and introducing no artifacts. Their work was based on the gradient domain methods which they generalized and extended to account for perceptual issues such as the sensitivity for suprathreshold contrast in HDR images. Mantiuk introduced a low-pass measure of contrast based on the logarithmic ratio G as the measure of contrast between two pixels, given by:

$$G^k_{i,j} = \log_{10}(\frac{L^k_i}{L^k_j}) \tag{2}$$

where L^k_i and L^k_j are luminance values for neighboring pixels i and j. The first step in the tone mapping process is to use the equation (2) to transform the luminance, obtained from the radiance map calculation in section 2 to contrast. The second step is to perform the inverse operation that restores an image from modified contrast values $\widehat{G}$. This can be achieved by minimizing the objective function, given by equation 3, and that reduces the distance between a set of contrast values $\widehat{G}$ that specifies the desired contrast, and G, which is the contrast of the actual image.

$$f(x^1_1, x^1_2, \ldots, x^1_N) = \sum_{k=1}^{K} \sum_{i=1}^{N} \sum_{j \in \Phi_i} p^k_{i,j} (G^k_{i,j} - \hat{G}^k_{i,j})^2 \tag{3}$$

where x^1_i is the contrast value of the i^{th} pixel on the finest level of the pyramid. Φ_i is the set of the neighbors of the pixel i, N is the total number of pixels, K is the number of levels in a Gaussian pyramid, and $p^k_{i,j}$ is a constant weighting factor. After getting the contrast information from pixel luminance values, it is transduced to the perceptually linearized visual response space to get response values of the HSV. A contrast mapping step is then applied on the resulting image to fit into the contrast reproduction capabilities of the display device (here the OLED HMD).

3 Application for the Visually Impaired

3.1 Visual Impairment

Visually impaired people suffer from significant limitations of visual capabilities depending on the strongly varying conditions of luminance in real-world environments. In normal vision, the retina contains two types of photoreceptors, rod and cone cells, and operates differently under distinct adaptation conditions. At high and medium average of luminance (photopic and mesopic conditions), visual functions such as acuity, contrast sensitivity and color discrimination, carried out by cones, are near optimal. At very low illumination (scotopic) level, cones do not have a sufficient sensibility and only rods are active, leading to substantially reduced acuity and contrast sensitivity. Night blindness (i.e dramatic decrease of visual acuity and contrast sensibility in mesopic and scotopic conditions) occurs when rod photoreceptors (as in retinitis pigmentosa) or optic nerve (as in glaucoma) are damaged [27]. The cone degeneration (macular degeneration and RP) strongly lowers the glare threshold and leads to photoaversion The visual adaptation to the variation of light is also slowed, as compared to normal vision : changes of luminance levels over time (from dark room to a lightened room and vice versa) can lead people to express discomfort, or even pain for a sudden and extreme change of illumination.

In order to help patients suffering from RP and Glaucoma to cope with their light sensitivity, we intend to design a new type of specialized "electronic googles" : Wear opaque glasses that completely cover the eyes allows the visually impaired to be protected against the external high luminosities. The only source of light comes from the HMD display, which can be controlled via tone mapping operator to match the user's comfort range of luminosity. On the other hand, dark areas in the real scene may be displayed with more contrast, in order to ease their comprehension.

3.2 System Architecture

The wearable aid system that we propose is composed of two major devices: a single digital camera and an advanced technology of commercialized HMD device. Fig. 1 illustrates the major components of the system. The camera is fixed on the top of the HMD, and used for data acquisition of the ambient scene. Acquired data pass through image processing pipeline build to generate HDR images. The resulting images are then displayed on the HMD screen.

Digital Camera. The camera we use is a CMOS image sensor that reaches a maximum resolution of 1920×1080 at a rate of 30 frames per second (fps) in YUY2 data output format, where YUY2 is a raw video encoding format in the family of YUV formats that encodes color images taking into account human perception, in the sense that it stores the color information the same way human brain works. Since human has finer spatial sensitivity to luminance or "luma" (black or white) differences than chromatic (color) differences, YUY2 is a type of YUV of color space representation that samples the luma (Y) once every pixel but only samples the chroma (U(Cb) and V (Cr)) once every horizontal pair of pixels. To control the exposure duration, the camera has a shutter speed that ranges from 2.10^{-4} to 1 second.

Head Mounted Display. For design prototyping we use as test platform the zSight professional head mounted display, characterized by a set of properties such as a high resolution full-color SXGA 1280×1024 pixels per eye, a 60 binocular field of view, a 24 bit of color depth encoding. The device screens are designed with the new organic light-emitting diode (OLED) technology, enabling to achieve a high contrast ratio of 10000:1 from highlights to shadows. This HMD is an occlusive device that isolates completely the user from the real wold. For better wearing comfort, the HMD is equipped with a adjustable binocular to fit the inter-pupillary distance (IPD), as well as an adjustable focus for each eye using the outer lens rings.

Using a spectrophotometer, a physical calibration procedure has been performed for light and color measurement of the HMD screens with pre-fixed parameters settings of the display (i.e brightness, contrast). This HMD profiling and calibration is needed for a better control of how this device produces colors and light energy.

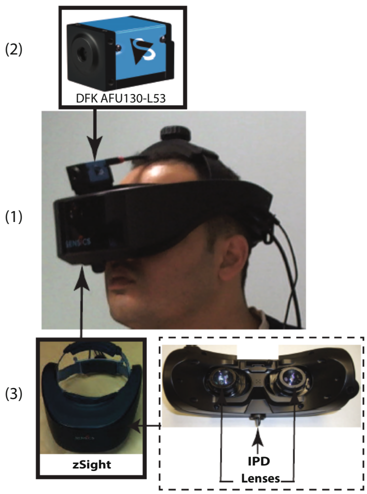

Fig. 1. (1) Portable real world HDR imaging system composed of: (2) a digital camera, (3) an OLED HMD using binocular system equipped with mechanical adjustment for inter-pupillary distance (IPD) and for focus (± 4 diopters) for each eye

3.3 HDR Image Generation for the Visually Impaired

In this work we derive the Mantiuk's framework in order to perform tone mapping with a better image representation which would models the Human Visual System (HVS) performance. Simulating the HSV perceptual effects during the tone mapping process conveys a realistic impression of HDR data over a wide range of luminance, when such data are displayed on typical display devices (e.g OLED). This framework exploits Peli's study [26] which shows that contrast discrimination sensitivity, especially of complex images, is highly dependent on spatial frequency. Thus the definition of local band-limited contrast is useful for determining nonlinear threshold characteristics of spatial vision in both normal observers and the visually impaired. The contrast processing technique presented in Section 2.3, that incorporates band-limited contrast definition to measure contrast as a difference between levels of Gaussian pyramid, is applied to design a contrast enhancement method for images that improves the local image contrast by controlling the local image gradient. Since that contrast enhancement plays a very important role in increasing visual quality of an image, this method is a major part of HDR image generation pipeline. This pipeline starts from live image sensor that acquires multiple images with different exposures, the obtained images are then combined to calculate the HDR radiance map. The computed radiance map is then used to derive a contrast enhancement, as a final step, the contrast values are mapped to display LDR images on the HMD screens. This contrast mapping does not intend to only fit HDR images to LDR displays, but we want also that the displayed images meet visual capabilities of visually impaired people. The Fig. 2 illustrates three raw frames acquired with a single camera at different exposures (low, medium and high) of a scene and the obtained HDR image. The first frame is acquired with a short shutter speed resulting in an under-exposed image, where details related to illuminated areas are highlighted. The second frame is taken with medium shutter speed, useful to enlarge the set of input frames and hence a larger dynamic range of the scene luminance is considered for our HDR image generation pipeline. As for the third frame, it is taken with a high shutter speed which gives an over-exposed image where details related to shadows and poorly illuminated areas of the scene are pointed out. The resulting frame is the HDR image that is contrast-mapped for the HMD display.

The main advantage of our system is that it displays contrast-enhanced images of the ambient scene independently from its luminance conditions. Besides, the HMD encloses the eyes and the visual field of the user, fairly enough to prevent light interference of external luminance with the HMD screen radiance. Hence it will help the visually impaired to achieve optimal vision performance. To provide effective assistance, our device has to be capable of controlling the brightness emitted by the display of the HMD in order to keep it within the visual comfort range of the user, which means between a level high enough to allow detection contrasts, and a level low enough so as not to cause glare or pain. More over, transitions between different levels of luminance have to be slow enough to allow the user's visual adaptation. Accurate knowledge of

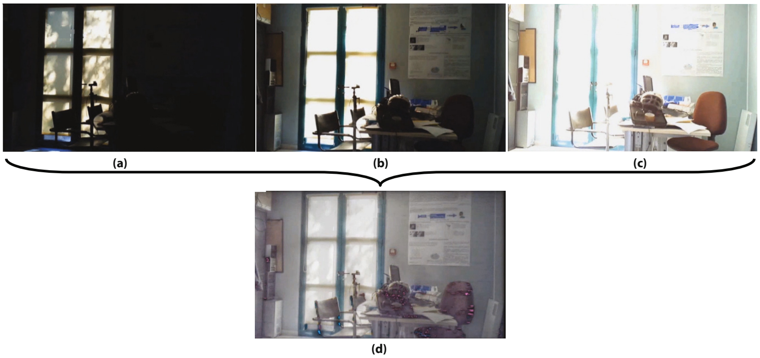

Fig. 2. (a) Under-exposed frame exploited to highlight details around the illuminated area (e.g. external tree shadow distinguished through the window door under daylight illumination), (b) frame with medium exposure used to enlarge the dynamic range inputs to the HDR image generation pipeline, (c) Over-exposed frame acquired to bring out hidden detail in the shadows and poorly illuminated areas, (d) LDR image output from our HDR image construction pipeline.

parameters such as visual comfort range of luminosity and visual adaptation speed within this comfort range, makes it possible to modify tone mapping operator to take into account visual capabilities of the user. These visual parameters are not measured quantitatively during classical orthoptic assessment, who study visual acuity, visual field, ocular motility, and color vision. Glare measurements exist [28] but are not exactly suitable for our study, as they are designed to measure visual performance under very high luminance levels. In the same way, measures of contrast sensitivity under scotopic conditions do not appear in normal procedure of low vision assessment. So we were led to design the specific psychophysical tests that allow us to measure these parameters. These test will be conducted once we have the agreement of bioethical commission.

4 Conclusion and Future Work

In this paper, we have proposed the concept of a wearable aid system for visually impaired people. The system is composed of a single digital camera and a commercialized HMD which can display realistic visual images of the environment acquired by the camera. The singularity of the displayed images is that they are the result of an HDR image generation pipeline, which combines multiple frames of the same scene at different exposures to generate an HDR image, this HDR image is the subject of a contrast mapping technique derived to obtain a displayable image on the LDR screens of the HMD. The HDR image processing technique is applied to enhance the contrast of the displayed images and intend to meet the visual capabilities of visually impaired people. These capabilities are described in terms of several parameters, assessed through specifically designed tests. To achieve contrast enhancements, local gradient luminance of images is controlled through a Gaussian pyramid representation structure.

In future, we plan to reduce the processing latency of our system, especially of the HDR image generation module which is time-consuming, in order to meet the unavoidable constraint of real time. Contrast has to be significantly enhanced for the high spatial frequencies [29] where greater reduction in sensitivity occurs. We would also like to study the color information and include a color enhancement module to our framework, using a representation similar to contrast enhancement based on the luminance information. Furthermore, technical concerns such as electrical consumption, weight and prizes of our wearable device will be investigated in a future work when proofs of efficiency are established.

Acknowledgments. This work was financially supported by Sopra Group for the larger part, and by Areva and Capgemini.

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