Smart lighting system with tunable radiation pattern

Jeroen Cerpentier[1,*], *Nick* Rondelez[1], *Nathan* Slembrouck[1], and *Youri* Meuret[1]

[1]KU Leuven, ESAT - WaveCoRE, Light & Lighting Laboratory, Gebroeders De Smetstraat 1, 9000 Ghent, Belgium

Abstract. Smart lighting systems are capable of producing light when and where it is needed. Such functionality can be achieved with adaptive optical systems, which consist of one or multiple adjustable components, enabling illumination with a variable radiation pattern. This paper introduces the design of a compact, tunable optical system, allowing illumination with variable beam size and beam direction. We demonstrate how this system can be combined with computer vision and a feedback loop, to achieve a fully autonomous, smart illumination system.

1 Introduction

LEDs have had a large impact on advancing society and research over the last years. However, despite their efficiency, they are still a significant energy consumer, causing high costs. This has led to the introduction of *smart lighting systems*, creating light when and where it is required, taking also comfort and safety into account [1, 2]. To achieve this, researchers have combined sensors with dimmable luminaires, adjusting the luminous flux based on environmental activity [3, 4].

A remaining problem is that the luminous intensity pattern is generally not matching the field-of-illumination of interest to the user. Modern day optical systems frequently integrate freeform optics, able of producing any arbitrary illuminance distribution [5, 6]. However, if the targeted distribution changes, the luminous intensity pattern can not be adapted because freeform optics are stationary components. This is a clear limitation in settings which are frequently reorganized. Such systems demand illumination with adaptive optical components.

Previous research and commercial applications have proposed various approaches for adaptive illumination with tunable radiation pattern. In particular, systems exist with variable beam size and/or direction [7, 8]. Ideally, lighting systems with tunable radiation pattern could be combined with computer vision, to achieve fully autonomous beam shaping. Such systems would also show great advantages over sensor-based applications, since computer vision is generally more robust [9, 10]. This paper gives an overview of a smart lighting system with tunable radiation pattern, with the functionality summarized in Figure 1a. It consists of a tiltable mirror, combined with a tunable diffuser to achieve variable beam deflection and beam size. This optical system is then combined with a computer vision algorithm, trained to detect certain target objects. After the detection, a feedback loop is deployed to match the resulting light spot of the adaptive luminaire with the detected object [11].

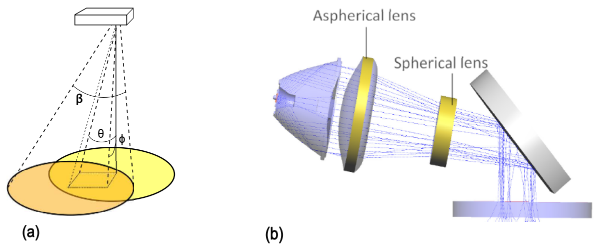

Figure 1. (a) Lighting fixture with tunable radiation pattern. The beam deflection angle (ϕ, θ) and beam size β can be adjusted. (b) The system in the software LightTools 8.7.0.

2 System overview

The proposed configuration consists of a sequence of optical components, each having their individual influence on how light is guided through the system. The emitted light from a high power LED is directed through a TIR lens, which collimates the light bundle, followed by an aspherical and spherical lens in sequence, which serve as focusing optics. Lastly, a tiltable mirror and tunable diffuser are used, and these are the *adaptive* components (Figure 1b). The tunable diffuser is liquid crystal-based; the size of the resulting beam depends on the supplied voltage. It is crucial to also note that this has an effect on the efficiency: the higher the degree of "beam enlargement", the more light is lost when passing through the diffuser.

*e-mail: jeroen.cerpentier@kuleuven.be

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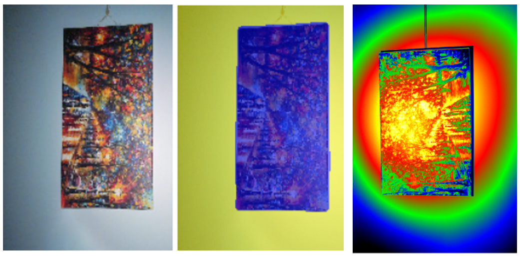

Figure 2. (Left) Picture taken by the microprocessor - (Middle) Segmentation map - (Right) Final illuminance measured with a luminance camera.

2.1 Detection and feedback loop

The system is equipped with a Raspberry Pi and camera. The camera detects an object, and the processor adjusts the mirror and tunable diffuser to direct the light towards the detection. We demonstrate the functionality in a museum setting, to achieve automatic painting illumination. Consider a computer vision algorithm that performs *image segmentation*, making a distinction between "background" and "painting". Then the model makes a segmentation map of a painting and knows where exactly it is located in the camera field-of-view (Figure 2).

Adjusting the lighting system, the processor drives the mirror by controlling engines, while also managing the tunable diffuser via PWM signals. The feedback loop initiates by putting the mirror and diffuser in neutral position. The beam deflection angle is adjusted to closely match the center of mass of the detected object. This is done by measuring the difference between the target spot and the current spot, and iteratively adjusting the beam by 1° in the desired direction until a stopping criterium is met. Afterwards, the spot size is adjusted via the tunable diffuser. This is done instantly, since the relationship between voltage and beam opening angle can be characterized in advance.

3 Discussion and conclusions

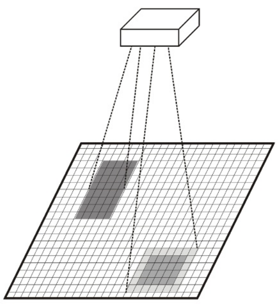

Figure 3. Selectively addressable LED arrays allow for flexible tailoring of luminous intensity distributions.

We presented an approach to achieving flexible smart lighting with variable radiation pattern. Based on an optical system with a tunable mirror and diffuser, the beam divergence angle and spot size can be adjusted. The optical system is combined with computer vision and a feedback loop, resulting in a fully autonomous lighting system for museum applications.

An alternative approach would be to replace the proposed lighting systems with a LED array. LED arrays have seen extensive usage in the automotive industry for adaptive car headlamps. In theory, it would be possible to extend this application to indoor lighting settings. Due to the pixelated nature of an LED array, a single LED array could be sufficient to achieve illumination of multiple objects at the same time (Figure 3). Especially LED arrays with a high pixel resolution (e.g. $\geq$ 1000 pixels) have the potential to serve as a single illumination source which can simultaneously illuminate multiple objects, even with more *exotic* shapes [12].

References

[1] J.S. Botero-Valencia, J. Valencia-Aguirre, D. Durmus, W. Davis, Energy and Buildings **199**, 579 (2019)
[2] T. Trop, S. Shoshany Tavory, B.A. Portnov, Environment and Behavior p. 00139165231163550 (2023)
[3] N.H. Moadab, T. Olsson, G. Fischl, M. Aries, Energy and Buildings **244**, 111009 (2021)
[4] I. Chew, D. Karunatilaka, C.P. Tan, V. Kalavally, Energy and Buildings **149**, 180 (2017)
[5] S. Kumar, Z. Tong, X. Jiang, International Journal of Extreme Manufacturing **4**, 032004 (2022)
[6] K. Desnijder, P. Hanselaer, Y. Meuret, Optics letters **44**, 771 (2019)
[7] L. Maghnagi, A. Tacchi, *Motorized spotlight with axially offset vertical arm* (US Patent US11204157B2019, 2019)
[8] N. Rondelez, W. Ryckaert, Y. Meuret, Lighting Research & Technology **53**, 345 (2021)
[9] F. Zantalis, G. Koulouras, S. Karabetsos, D. Kandris, Future Internet **11**, 94 (2019)
[10] A.K. Tripathy, A.K. Mishra, T.K. Das, *Smart lighting: Intelligent and weather adaptive lighting in street lights using IOT*, in *2017 International Conference on Intelligent Computing, Instrumentation and Control Technologies (ICICICT)* (IEEE, 2017), pp. 1236–1239
[11] J. Cerpentier, N. Rondelez, N. Slembrouck, S. Gielen, P. Acuña, Y. Meuret, Building and Environment p. 110552 (2023)
[12] J. Cerpentier, Y. Meuret, P. Acuña (2023)