BUDAPEST UNIVERSITY OF TECHNOLOGY AND ECONOMICS
FACULTY OF MECHANICAL ENGINEERING
PATTANTYÚS-ÁBRAHÁM GÉZA DOCTORAL SCHOOL OF MECHANICAL ENGINEERING
DEPARTMENT OF MECHATRONICS, OPTICS AND MECHANICAL ENGINEERING INFORMATICS

BERTALAN PIZÁG

ANALYSIS OF MOBILE PHOTOMETRIC AND LUMINANCE MEASUREMENT SYSTEMS

Thesis booklet

Supervisor:
Balázs Vince Nagy, PhD
associate professor

Budapest, 2023

1. INTRODUCTION AND OBJECTIVES

The novel technologies available for lighting design pose new challenges for standard metrology. However, new developments and technologies are also available to further push and expand the capabilities of photometric measurements.

The standard photometric quantities are derived from radiant power by compensating for the spectral sensitivity of the human eye, the so-called $V(\lambda)$, or spectral luminous efficiency [1] function. Mainly four base quantities are used for the characterization of light sources and lighting scenarios, namely luminous flux, illuminance, luminous intensity, and luminance. The first of these corresponds directly to radiant power [2], while the rest takes area, solid angle, or both [2] into accord.

The quantity of illuminance is the easiest to measure [3]. It is used for the simple characterization of lighting scenarios (e.g., indoor spaces [3]) due to not containing directional characteristics. The measurement can be carried out manually using a handheld device.

The measurement of luminous intensity has to adhere to much stricter standards and requires special laboratory instruments [3]. The process of the measurement is called goniophotometry, and its goal is to record the emission characteristics of the target in the form of a point source. This requires a positioning system with at least two independent degrees of freedom that can also provide a substantial distance from the target (ten times the diameter of the emissive area) [3]. The resulting luminous intensity distributions can be employed in traditional design calculations and simpler simulations [4].

To measure luminance, the detector has to be fitted with imaging optics that accumulates light emitted from the target in a given solid angle determined by the system's properties onto the detector [3]. Modern systems are akin to cameras, called ILMDs (Imaging Luminance Measurement Devices), that, instead of containing a single detector, provide an array of luminance values, one for each pixel. Measuring luminance is critical for evaluating various lighting scenarios [3], [4] due to being closely associated with human perception of light. If used for the characterization of light sources, it provides an extended model of emissions. Such datasets can be acquired through the non-standard [5] process called near-field goniphotometry [6], a relatively novel process that has been gaining attention throughout the past decade [7]. The application of luminance characteristics has multiple benefits but also comes with a set of challenges that must be addressed in this research.

All the above-mentioned processes are either time-consuming and labor-intensive or require special instruments to carry out. Processes of similar properties are nowadays prime subjects for drone-based automation [8]. Drones have been used in countless instances to capture images for the purpose of industrial or agricultural inspection; on occasion, they have been used for special photometric measurements as well [9]–[11].

The dissertation centers around drone-based measurement systems capable of recording various photometric quantities, with luminance being the focus of the research. The research can be split into three domains: the qualification of luminance measurement systems, the evaluation of drone-based systems for photometric measurements, and the error correction of the recorded luminance distributions.

Multirotor drones provide an easy-to-navigate, precise platform [12] that can be adapted for various lightweight applications. Throughout the dissertation multiple configurations are presented for the measurement of illuminance and luminous intensity/luminance.

The main limiting factor of drone-based systems is the device's maximum load-bearing capacity. The small devices required for indoor operations cannot carry larger detectors, which might be necessary for proper luminance measurements, and in their place smaller cameras must be used. Using general-purpose cameras for light source measurements, however, can lead to several problems. Since the sensitivity of these cameras is designed for substantially lower light levels, detector saturation can not necessarily be avoided even with the smallest aperture and exposure settings, necessitating the use of various filters. Said filters, however, introduce further complexity to the system, as their spectral characteristics heavily influence the results and can introduce further imaging errors. Small aperture settings also contribute to imaging issues, as the radical intensity of a light source leads to the appearance of extensive diffraction patterns [13]. In radical cases, where for example, both the measurement and the navigation rely on the same camera, it is well within the expectation that both saturation and the diffracted patterns will be present. The last section of the dissertation focuses on the reconstruction of such images.

2. RESEARCH METHODS

2.1. Drone-based measurement platform

The feasibility of the drone-based measurement platform can be presented by the evaluation of its positioning capabilities. For this reason, models must be constructed describing the various measurements.

The illuminance measurement can be easily implemented by outfitting the drone with a vertically positioned photodetector, although absolute position data have to be provided by other means.

In the case of luminance intensity measurements, the detector always needs to be pointed toward the targeted light source. Since the drones can only maintain a stable position in a horizontal state, the detector has to be mounted on a motor-tiltable module. Furthermore, to properly aim the detector, a camera is required next to it, with both of their axes aligned. Such a system can determine its own position in relation to the light source based on its height and the drone's altitude and orientation measurements.

Similar systems can be used for the measurement of luminance if the targeting camera is replaced by a suitable, radiometrically calibrated sensor.

Based on these considerations, it can be stated that the illuminance measurement system's precision inherits the precision of the drone's positioning system. In contrast, the system used for luminance intensity measurements has a more complex relationship between the positioning and measurement uncertainties. Modeling the drone in various static positions over the workspace, the contribution of various sensors can be evaluated using the partial derivates of the projective model. The results can be used to determine which parts of the workspace contain higher levels of positioning uncertainty.

The models for both illuminance and luminous intensity measurements were validated by experiments using a modified Parrot AR.Drone2 device. The results provided by this simple prototype fall far behind the capacity of professional drone technology. Even then, the illuminance measurements could be performed within a passable margin, and while luminous intensity measurements were loaded with various noise effects, their results correlated with the calculations.

2.2. Qualification of near-field goniophotometers

Due to the lack of standardized requirements for near-field goniophotometers used for the measurement of luminance distributions, the second part discusses methods for evaluating their precision and reliability.

The experiments rely on a simulated measurement model that samples customizable distributions using a virtual camera. The system can be configured with various distance and camera properties and has two rotational axes to move the camera around, allowing it to test different configurations. Positioning uncertainties can be simulated on the rotational axes and the placement of the light source.

The simulation is capable of producing a substantial number of measurement samples, enabling the use of the Monte Carlo method for the evaluation of uncertainties [14]. For each configuration, multiple sets of data are simulated using pseudo-random number generation to model positioning uncertainties. The results can be analyzed through statistical means to evaluate the sensitivity of the system.

Based on these experiments, multiple indicators are proposed for the evaluation of near-field goniophotometers, along with recommendations for geometrical constraints.

2.3. Correction of luminance images

Cameras capable of luminance measurements resolve the high contrast differential of the light source and the background using multi-exposure high dynamic range (HDR) images. In a non-ideal situation, however, the high peak intensity can lead to various imaging errors and artifacts. The dissertation focuses specifically on reconstructing small, saturated regions due to their frequent appearances in simpler devices or in specific situations where short exposures are not feasible (e.g., flickering sources).

The experiments have been conducted in laboratory conditions, capturing images of halogen and LED sources. Each of the images has been created using the same camera and optics but with different aperture settings. To provide reference values for the measurements, the raw images are not saturated; instead, the effect of saturation is algorithmically simulated.

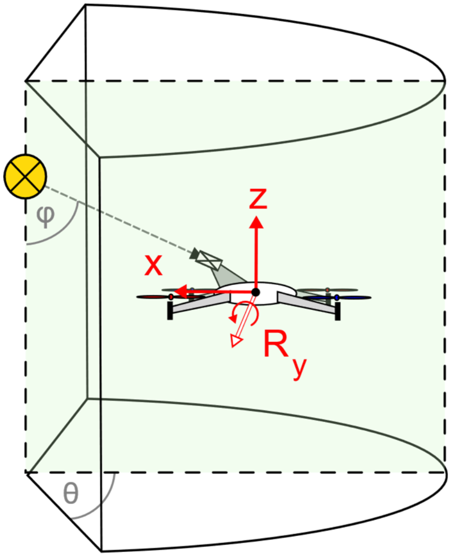
Due to the hexagonal aperture of the objective, an easily recognizable star pattern is present around the light sources. Using this pattern, it is possible to construct an image processing algorithm that can recognize the orientation and locate the center of the light sources. Then sections of the arms can be extracted for further analysis.

Using sections of the images reduces the dimensionality of the problem; therefore, simple functions can be fit to the data to estimate the original peak value.

Various functions can be used for the estimation, including simple polynomial fractions or more complex models of the Fraunhofer-diffraction in different forms [15], [16]. Due to the high levels of noise present in the images, multi-parameter models cannot be fit onto the data reliably. However, calibrating for the camera-specific constants of the model makes the estimation of the peak intensity possible.

3. NEW SCIENTIFIC RESULTS AND THESES

I. THESIS: Taking a drone-based photometric measurement system that uses the light source as a positional reference and a camera for targeting and positioning, the following can be stated regarding its positioning uncertainties. The degrees of freedom outside of the vertical plane of the measurement model can be ignored, meaning that only the axes in the vertical plane (x, z), and the rotation around their common normal (R_y, pitch) must be considered for the system's evaluation, as represented in the following figure:



Related publications: [P1], [P5]

II. THESIS: Taking a drone-based photometric measurement system that uses the light source as a positional reference and a camera for targeting and positioning, the following

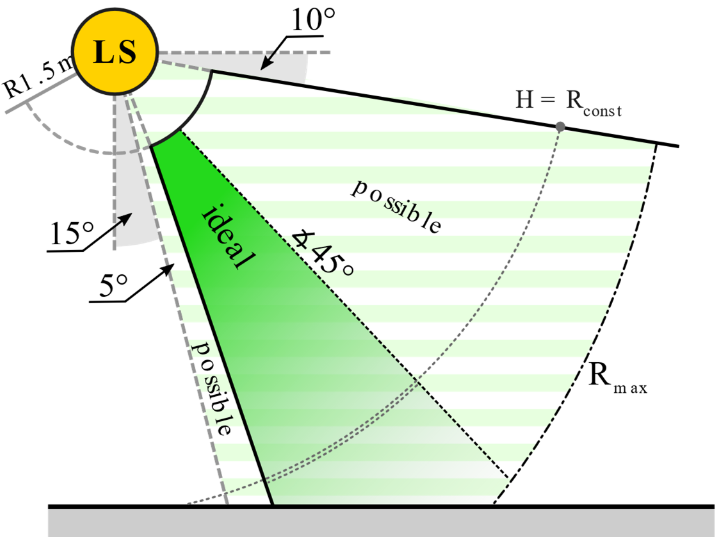
can be stated regarding its positioning uncertainties. In each position of the measurement space, the positioning error does not exceed the mean value by more than three standard deviations if the following requirements are fulfilled:

- The angle between the direction of the measurement and the horizontal plane is at least 10°.
- The angle between the direction of the measurement and the vertical axis is at least 15°.
- The device is placed at least 1.5 meters from the light source.
- The device is placed at a distance from the light source so that it can be recognized in the image as an extended object with a diameter of at least 3 pixels (R_{max}).

It can be further stated that the positioning uncertainties are the smallest when these further requirements also apply:

- The angle between the direction of the measurement and the horizontal plane is at least 45°.
- The angle between the direction of the measurement and the vertical axis is at least 20°.

The following figure illustrates these boundaries in the vertical section of the measurement:



Related publications: [P1], [P5]

III. THESIS: The positioning uncertainties of a near-field goniophotometer do not influence the measurement's repeatability if, for every subsample of at most 5° width in the recorded luminance distribution, there is a significant linear connection between the repeated instances.

The positioning errors influence the results through a spherical projection, leading to a non-linear relation between the displacement and the luminance data. Therefore, if a strong linear connection is present between repeated sets of data, it shows that positioning errors do not significantly influence the results.

The 5° wide subsamples are sufficient for relatively smooth distributions where the gradient of the normalized distributions is within ±1. For *distributions containing steeper intensity changes, more dense sampling is required, or the affected regions must be omitted from the analysis.*

Related publications: [P2], [P4]

IV. **THESIS: In a near-field goniophotometric measurement, the luminance of a light source is recorded on a virtual sphere (envelope) around the target. The diameter of this sphere must be large enough so that no rays that connect the source and the camera will have an angle of incidence on the envelope larger than 45°. This can be achieved if the envelope is 50% greater than the largest diameter of the light source.**

Since the positioning errors have a substantial effect above 45° incidence, the omission of such angles from the luminance distribution reduces their effect significantly.

Related publications: [P2], [P4]

V. **THESIS: The angular positioning error of near-field goniophotometers is negligible compared to the positioning of the target source. This relation can be expressed as follows:**

$$E_{pos}\left(R \cdot sin(\varepsilon)\right) \gg E_{ang}(\varepsilon)$$

Where R is the length of the instrument, ε is an angular value, while E_{pos} and E_{ang} are the positional and angular errors.

Related publications: [P2], [P4]

VI. THESIS: The peak intensity in a saturated image of a point-like light source can be estimated within the $10^{\log(I_0)\pm 0.5}$ range by fitting the following function to the sections of the diffracted pattern along the r radial coordinate:

$$f(r) = \begin{cases} f_1(r) = \dfrac{1}{(ar+b)^4} + c & \left|\dfrac{\partial f}{\partial r}\right| \geq \tan(89.75°) \\ f_2(r) = er + f & \left|\dfrac{\partial f}{\partial r}\right| \leq \tan(89.75°) \end{cases}$$

where:

$$f_1(r_{crit}) = f_2(r_{crit}) \text{ és } \dot{f}_1(r_{crit}) = \dot{f}_2(r_{crit}),$$

furthermore, a, b and c are identified parameters, r_{crit} is the common point of the two functions at $89.75°$ steepness, and I_0 is the real intensity peak.

Related publications: [P3]

VII. THESIS: In a saturated image created by a camera with a hexagonal aperture, the peak intensity can be estimated within the range of $[0.5I_0; 1.5I_0]$ if the spectral distribution of the source is known and within $[0.5I_0; 2I_0]$ if it is not available, by fitting the following function if the arms of the diffracted pattern:

$$I_\lambda(\tau) = \frac{64}{81}\frac{I_1}{x^4}\left(\frac{\sqrt{3}}{2}\mathrm{x}\sin\left(\frac{\sqrt{3}}{2}x\right) - \cos\left(\frac{\sqrt{3}}{2}x\right) + 1\right)^2 \quad , \quad x = \frac{2\pi}{\lambda}\tau R$$

$$I(\tau) = \frac{\sum w_\lambda \cdot I_\lambda(\tau)}{\sum w_\lambda}$$

where I_0 is the real intensity peak, I_1 its identified value, $0 \le \tau \le 1$ is the ratio of the radial coordinate and the radius of the screen, λ is the wavelength, w_λ is the combined spectral sensitivity of the camera and the spectral distribution of the light source, and R is a camera-specific calibrated value.

Related publications: [P3]

4. RELATED PUBLICATIONS

[P1] B. Pizag and B. V. Nagy, “Quadcopter Based Automation of Photometric Measurements,” in 2018 IEEE 18th International Power Electronics and Motion Control Conference (PEMC), 2018, pp. 864–869, doi: 10.1109/EPEPEMC.2018.8521871.

[P2] B. Pizág and B. V. Nagy, “Propagation of positioning uncertainties in near-field goniophotometers using the Monte Carlo method,” Appl. Opt., vol. 59, no. 13, p. 4055, May 2020, doi: 10.1364/AO.386451.

[P3] B. Pizág and B. V. Nagy, “Extrapolation of Saturated Diffraction Spikes in Photographs Containing Light Sources,” Period. Polytech. Mech. Eng., vol. 64, no. 3, pp. 233–239, Jun. 2020, doi: 10.3311/PPme.16044.

[P4] B. Pizág and B. V. Nagy, “Fénysűrűség karakterisztika mérési pontosságának vizsgálata Monte-Carlo szimulációval,” in XXX. Nemzetközi Gépészeti Konferencia – OGÉT 2022, 2022.

[P5] B. Pizág, D. Kacz, and B. V. Nagy, “A drone-based photometric measurement platform,” J. F. Robot., vol. 39, no. 8, pp. 1218–1230, Dec. 2022, doi: 10.1002/rob.22105.

5. REFERENCES

[1] CIE, "Commission Internationale de l'Eclairage Proceedings, 1924," 1926.

[2] CIE, "ILV: International Lighting Vocabulary, 2nd Edition," 2020. doi: 10.25039/S017.2020.

[3] EN, "EN 13032-1, Light and lighting - Measurement and presentation of photometric data of lamps and luminaires - Part 1: Measurement and file format," Brussels, 2004.

[4] EN, "EN 13201-1, Road lighting - Part 1: Selection of lighting classes," Brussels, 2004.

[5] CIE, "CIE S 025/E:2015, Test method for LED lamps, LED luminaires and LED modules," 2015.

[6] I. Ashdown, "Near-Field Photometry : A New Approach," *J. Illum. Eng. Soc.*, vol. 22, no. 1, pp. 163–180, 1993, doi: 10.1080/00994480.1993.10748029.

[7] M. López, K. Bredemeier, N. Rohrbeck, C. Véron, F. Schmidt, and A. Sperling, "LED near-field goniophotometer at PTB," *Metrologia*, vol. 49, no. 2, 2012, doi: 10.1088/0026-1394/49/2/S141.

[8] R. Merkert and J. Bushell, "Managing the drone revolution: A systematic literature review into the current use of airborne drones and future strategic directions for their effective control," *J. Air Transp. Manag.*, no. 89, 2020, doi: 10.1016/j.jairtraman.2020.101929.

[9] D. S. D. Sitompul, F. E. Surya, F. P. Suhandi, and H. Zakaria, "Runway Edge Light Photometry System by Using Drone-Mounted Instrument," in *Proceeding - 2019 International Symposium on Electronics and Smart Devices, ISESD 2019*, 2019, doi: 10.1109/ISESD.2019.8909498.

[10] X. Li, N. Levin, J. Xie, and D. Li, "Monitoring hourly night-time light by an unmanned aerial vehicle and its

implications to satellite remote sensing," *Remote Sens. Environ.*, vol. 247, no. April, 2020, doi: 10.1016/j.rse.2020.111942.

[11] P. Fiorentin, C. Bettanini, and D. Bogoni, "Calibration of an autonomous instrument for monitoring light pollution from drones," *Sensors (Switzerland)*, vol. 19, no. 23, 2019, doi: 10.3390/s19235091.

[12] G. Ajay Kumar, A. K. Patil, R. Patil, S. S. Park, and Y. H. Chai, "A LiDAR and IMU integrated indoor navigation system for UAVs and its application in real-time pipeline classification," *Sensors (Switzerland)*, vol. 17, no. 6, 2017, doi: 10.3390/s17061268.

[13] J. W. Goodman, *Introduction to Fourier Optics*, 2nd ed. The McGraw-Hill Companies, Inc., 1996.

[14] R. Y. Rubinstein and D. P. Kroese, *Simulation and Monte-Carlo method*, 2nd ed. John Wiley & Sons, Inc., 2008.

[15] J. Komrska, "Fraunhofer Diffraction at Apertures in the Form of Regular Polygons. I.," *Opt. Acta Int. J. Opt.*, vol. 19, no. 10, pp. 807–816, Oct. 1972, doi: 10.1080/713818504.

[16] R. C. Smith and J. S. Marsh, "Diffraction patterns of simple apertures," *J. Opt. Soc. Am.*, vol. 64, no. 6, p. 798, Jun. 1974, doi: 10.1364/JOSA.64.000798.