Compact optical system for projection of dynamic safety patterns in cobot workspaces

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We present a low-cost optical system for projecting dynamic safety borders around a robotic arm. Pixelated white LED source is used, so the patterns can be recognized by the control system and be visible to human workers in real-time. The system has low f/# for large projected flux and ±18.5° FOV, which ensures projection of safety zone with sufficient area and sharpness of the patterns.

1 Introduction

As factory automation increases, humans and robots are sharing workspaces more frequently. To ensure safety, it's important to have visible indication of the robot's working area, as well as automatized safety protocols. Commercially available projectors can be used for this purpose, but they are often too large and expensive for widespread use.

We propose a simple optical system, which offers a compromise between its cost and resolution of the patterns' structures. The system consists of stock collection lens and custom-made symmetrical imaging asphere. Simplicity of the system enables its cost-efficient upscaling for the use in large area facilities.

2 Operation principle

Complete safety system consists of a two-lens projector, which works in tandem with a machine-vision camera (Fig. 1). Projection optics images flexible dynamic border, generated by white pixelated LED, around the operating robotic arm, while the camera recognizes any perturbation of this border, whether it is a shadow formed by a human hand, or another object that changes the trajectory of light reflected towards the camera lens [1].

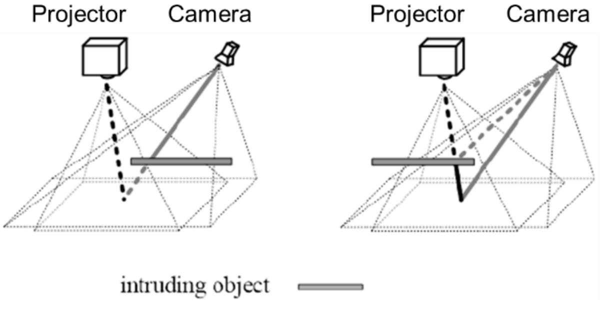

***Fig. 1** Principal scheme of the complete safety system [1].*

3 Light source

As light source we have used a prototype of pixelated white LED – Eviyos 2.0, developed by OSRAM for the use in dynamic automotive headlights. The LED has pixel pitch of 40 µm and consists of 25600 pixels in total, clustered in 1:4 ratio. Given pixel size enables high resolution of the beam and sufficient flexibility in pattern generation, however, to resolve such fine pixel, a complex color-corrected projection system is required [2], which is not applicable in our case due to the low-cost limitation.

4 Optical system design

For the optical design several main targets were given, as:

- Nominal projection distance of 5 m.
- as low as possible f/# for high output flux.
- Low distortion of ~1% max.

White light spectrum of the LED ensures comfortable perception of the patterns by humans, however, due to performance peak of the camera in the blue range, the main design wavelength is 460 nm.

Designed system is shown in Fig. 2. With achieved focal length of 20 mm, it ensures magnification of 250^{X} and diagonal FOV of ±18.5°. The system has variable iris, which changes f/# within 1.7…3.5 range for adjustment of the patterns' brightness w.r.t. the background illumination.

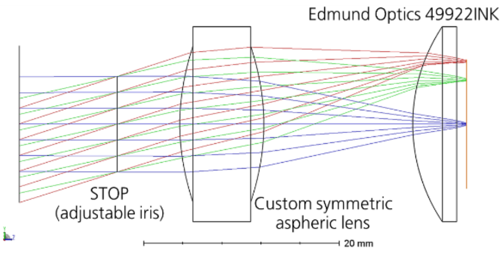

***Fig. 2** Projection system layout (shown in backtrace)*

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Lateral extent of the projection zone at 5 meters is 3.2 x 0.8 m², which means that for larger areas more than two projectors will be required. Adjacent projection zones pitch of two or more projectors wouldn't be a safety-ensuring solution, due to blind zones between their FOVs at a certain height caused by image space non-telecentricity. These blind zones must be avoided at least within the height of 2 meters from the working surface, meaning that sufficient overlap of the neighboring FOVs is required (Fig. 3). As result, 9 projectors are needed to achieve 3.2 x 0.8 m² as completely safe area.

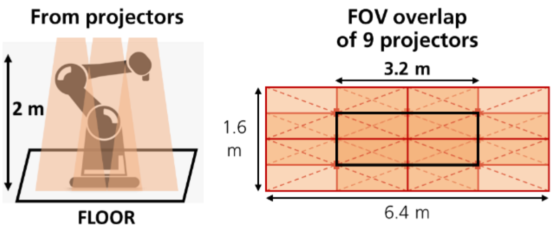

Fig. 3 *FOV overlap of 9 projectors.*

Due to quite limited aberration correction capabilities of such simple optics, its resolution is not high enough to sharply image every single pixel of 40 µm (corresponds to ~0.1°). Even for the highest f/# configuration (f/3.5), the RMS spot diameter exceeds pixel size more than 2.5 times, which is problematic for both: stability of patterns' recognition, as well as their adequate imaging. To solve this problem, several pixels can be combined into larger ones, i.e., enlarging the object size for the optics. In combination with f/# control, different pixels' combinations can be applied to find a compromise between brightness and sharpness of the patterns. Fig. 4 shows a test pattern created for the recognition simulation with a nominal combination of f/2 and 8 x 8 pixels combined into one, giving a single tile size of 80 x 80 mm².

Fig. 4 *Test pattern with f/# = 2 and 8 x 8 pix combined*

Max. distortion and shape deformation due to keystone effect is 1.3%, which is sufficient for correct FOV overlap of the neighboring projectors.

5 Characterization

Brightness, system transmission and size of the imaged tiles were evaluated with the built demonstrator. Fig. 5 shows a luminance picture of the corner tile for f/2 & 8 x 8 pix configuration. FWHM of real tile at 3.7 m projection distance is 55 x 52 mm², ~10% smaller than paraxial size (60 x 60 mm²), which corresponds to the simulations. System transmission of ~7% was measured for f/2 (~12% with f/1.7) as ratio between output flux of the "naked" LED and with optical system. Illuminance of the patterns couldn't be measured directly, due to very limited output flux of the prototype LED, however, extrapolation to the LED datasheet driving current and its output flux gives a level of ~500 lx from a single projector, enabling ~2000 lx from 4 overlapping FOVs, when 9 projectors are applied. Thus, the full system should provide sufficient brightness of the patterns even in a well-lit environment.

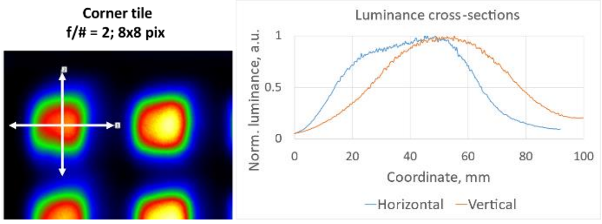

Fig. 5 *Luminance picture of the corner tile (f/2, 8x8 pix)*

The recognition test of the safety border interruption was done with a single projector. Despite quite limited brightness of the used LED, even with one projector, the camera could successfully detect the disruption of the safety border by a human's hand and the "Stop" command was immediately sent to the robotic arm (Fig. 6).

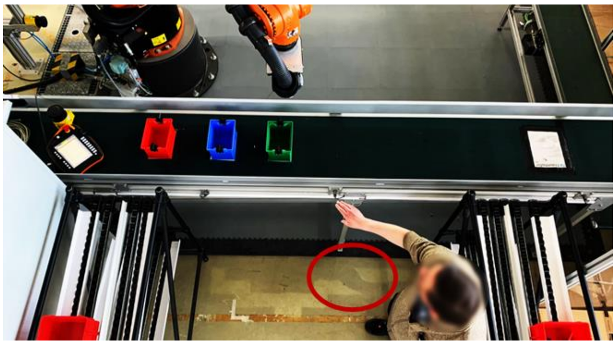

Fig. 6 *Operation-check of the system with one projector*

Conclusion and outlook

We have shown that matrix micro-LEDs are suitable not only for automotive applications, but also for the industrial safety projection and indication. Even with simple optics, first-generation system is realized with sufficient imaging quality for stable patterns recognition. The system can be easily scaled up for mass production and the resulting patterns will be well-received by humans.

References

[1] C. Vogel, C. Walter, N. Elkmann, *Safeguarding and Supporting Future Human-robot Cooperative Manufacturing Processes by a Projection- and Camera-based Technology*, Procedia Manufacturing 2017, v.11, (p.39-46).

[2] P. Brick, A. Günther, S. Grötsch, *Projection optical system with a pixelated µLED source for automotive applications*, Proc. SPIE 12078, IODC 2021.