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# Compact and high-brightness helmet-mounted head-up display system by retinal laser projection

Thibault North, Mathieu Wagner, Stéphane Bourquin, and Lucio Kilcher

***Abstract*—A compact binocular head-up display integrated in a motorcycle helmet is presented and characterized. The use of a laser micro-projector using a 2D MEMS-mirror enables the formation of a bright image, superimposed on the user vision. A fully-functional and adjustable 3D-printed prototype, thereby fitting the morphology of most users, is presented.**

***Index Terms*—Heads-up displays, system design, optomechanics, first-order optics**

## I. INTRODUCTION

HEAD-mounted displays (HMDs) have been a topic of interest for the last few decades, and their use in areas such as avionics and medicine is widespread, or at least desired [1]–[7]. Furthermore, the ubiquity of portable devices and the trend towards wearable computing reawakens the interest for lightweight HMD systems. In the last few years, HMD designs have been reported and industrialized mostly in the form of glasses, which superimpose information over the user's field of vision (FOV) via optical components such as beam-splitters, wedge prisms, or other kinds of free-form elements [8]–[10]. The design of such optical systems is challenging since it must meet several criterion: HMDs must feature a high brightness, preserve the user FOV, be adjustable, and provide a virtual image of a decent size with minimal fatigue for the user. The virtual image must be visible within a sufficiently large eyebox especially when there is a relative movement between the HMD and the user head [11]. HMD systems designed for augmented reality must display a wide-angle image approaching the eye FOV so that virtual objects or information can be mapped to objects of the real-world view [12]–[15]. On the other hand, other kinds of HMD systems are designed for hand-free interaction with electronic devices. In this case, a narrower FOV is sufficient, and such systems are potentially less invasive [16]–[18]. Helmet-mounted display systems (HMDSs) belong to the latter case, and strictly require that the user FOV remains cleared of all bulky optical element: the FOV must be cleared on at least $210°\times52°$ according to UN recommendation E/ECE/TRANS/505 No. 22, and for security purposes, no optical component should be close to the user eyes.

In this paper, we report a new non-obtrusive and high-brightness binocular HMDS targeting motorcycle users. To the best of our knowledge, no HMDS meeting all the requirements described above was reported so far. Livemap (livemap.info) is preparing a monocular HMDS for motorcyclists. Their optical system is located on top of the helmet, expanding its height and decreasing in particular the vertical FOV. Livemap nevertheless claims that this design satisfies the UN regulation mentioned above. Skully (skully.com) has also designed and sells a monocular HMDS for motorcyclists, forming a virtual image on an edge of the user vision. Nuviz (ridenuviz.com) prepares a similar HMDS, and Daqri (daqri.com) develops a binocular HMDS for human-machine interaction. In fact, such systems are often limited by their luminosity, since they relay a screen image formed by light-emitting diodes (LEDs). Also, those designs are not always binocular or dramatically reduce the user FOV. Most reports of HMDSs, despite not always targeting motorcycle users, require bulky optical components which can hardly be integrated inside a commercial motorcycle helmet without conflicting with its security padding elements [19], [20]. In this work, the inclusion of a MEMS-based laser micro-projector from Lemoptix permits the visualization of an ultra-bright image, visible in daylight conditions. The laser directly scans the retina of the user [21], [22], and therefore is not subject to unwanted speckle, contrary to systems transmitting a laser projected image onto a screen. The tight adjustment of the helmet on the head, as well as the alignment knobs guarantee that the user eye remains in the virtual image eyebox. The presented design is compact, and will fit inside a commercial helmet without substantial modifications. Moreover, contrary to previous work, the HMDS consists of a module attached to the bottom of the helmet, therefore letting the user FOV unaffected and preserving the safety components of the helmet.

A simple yet efficient optical design based on widespread optical components, as well as a fully functional prototype are presented.

## II. DESCRIPTION OF THE OPTICAL SYSTEM

The simplified optical design under study is depicted in Fig. 1(a) and (b). It consists of a pair of convergent achromatic lenses, in a Keplerian telescope configuration. Initially, the beam consists of parallel rays from a RGB laser micro-projector from Lemoptix [23], displaying a 4:3 image with a full projection angle of $2\alpha = 30°$, and facing a first converging lens $l_1$. This lens is followed by a second converging lens $l_2$, ensuring that the output beam also consists of parallel rays: in this case, the image is perceived at infinity. Satisfying this constraint requires that the distance $\overline{l_1 l_2}$ equals the sum of the focal lengths $f_{1,2}$ of $l_{1,2}$. In such a configuration, rays

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from different angles in the range $-\alpha \,..\, \alpha$ then intersect at a distance $g$ of $l_2$, where the user eye stands. For a binocular system, this condition must be met for each eye, with an adequate inter-pupillary distance. The optical arrangement depicted in Fig. 1(b) is designed. Dielectric mirrors are used to increase the compactness of the system, and to redirect the projected images towards each eye, via two arms $A_{1,2}$. Initially, the distance $i_p$ between these two arms is set to an inter-pupillary distance of 65 mm [19], [24]. In order to match every user's physiognomy, $i_p$ is adjustable within $\pm 10$ mm. The distance $\overline{l_1 l_2}$ is adjustable accordingly in order to preserve or adjust the focus. Moreover, mirrors $M_1$ and $M_2$ can be tilted around axes $y$ and $\vec{e_x} \pm \vec{e_z}$ to adjust the relative position of each image. Finally, an additional degree of freedom is provided to adjust the eyebox position in the $z$ axis. Using the small-angle

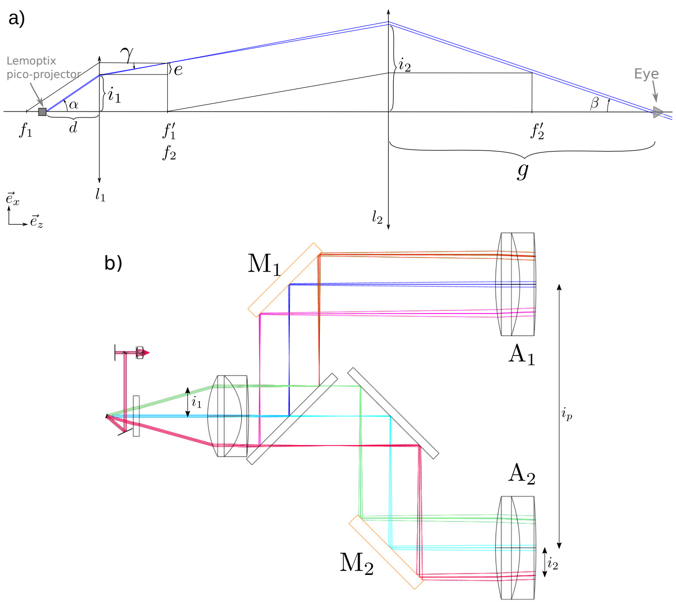


Fig. 1. Optical schematic of the system. (a) simplified ray tracing, (b) two arms layout.

approximation, valid for a half projection angle of $\alpha = 15°$, adequate values for the lens diameters as well as their focal lengths can be retrieved. The projected image is seen under an angle $\beta = \alpha f_1/f_2$, and hence only depends on the projection angle and the focal ratios. The effective required half-width $i_1$ on lens $l_1$ depends only on $\alpha$ and $f_1$. Similarly, the required half-width $i_2$ on lens $l_2$ depends on the focal lengths $f_{1,2}$, as well as the distance $d$ between the projector and lens $l_1$, as written in Eqs. (1) and (2):

$$i_1 = \tan(\alpha) d \approx \alpha d \tag{1}$$

$$i_2 = i_1 + \tan(\gamma)(f_1 + f_2) \approx \alpha d + \gamma(f_1 + f_2) = \alpha \left( f_1 + f_2 - d\frac{f_2}{f_1} \right) \tag{2}$$

with:

$$\gamma = \arctan\left(\frac{e}{f_1}\right) \approx \frac{e}{f_1} = \alpha \frac{f_1 - d}{f_1} \tag{3}$$

Moreover, the distance $g$ from the second lens $l_2$ at which the rays from the projector intersect is fully determined by the focal lengths $f_{1,2}$ and the projector distance $d$ to the lens $l_1$. The eyebox position in the $z$ direction can therefore be adjusted by shifting the projector along $\vec{e}_z$, so that $g$ is given as a function of $d$, without affecting $\beta$. Likewise, given two fixed focal lengths and lens sizes, the distance $d$ can be determined from the effective half-width on lens $l_2$:

$$g \approx f_2 + \frac{f_2^2}{f_1} - d\frac{f_2^2}{f_1^2} \tag{4}$$

$$d \approx \frac{f_1}{f_2}\left( f_1 + f_2 - \frac{i_2}{\alpha} \right) \quad \text{with } i_2 > i_1 \tag{5}$$

The HMDS reported in this work displays an image of $7° \times 5°$ in the bottom part of the user field of vision, for safety reasons. Initially, the projector is placed such that $d = f_1$, so that the beams converge at $f_2$. The focal lengths are $f_1 = 20$ mm, and $f_2 = 90$ mm. Using (2)–(5), the width of $l_2$ as well as the eyebox position are computed, and leads to $i_1 = 5.2$ mm, and $i_2 \in 4.05 \,..\, 6.41$ mm, $g \in 70 \,..\, 110$ mm when $d \in 21 \,..\, 19$ mm. Consequently, the 3D-printed mechanical system of Fig. 2 is designed. Its specifications are summarized in Table I.

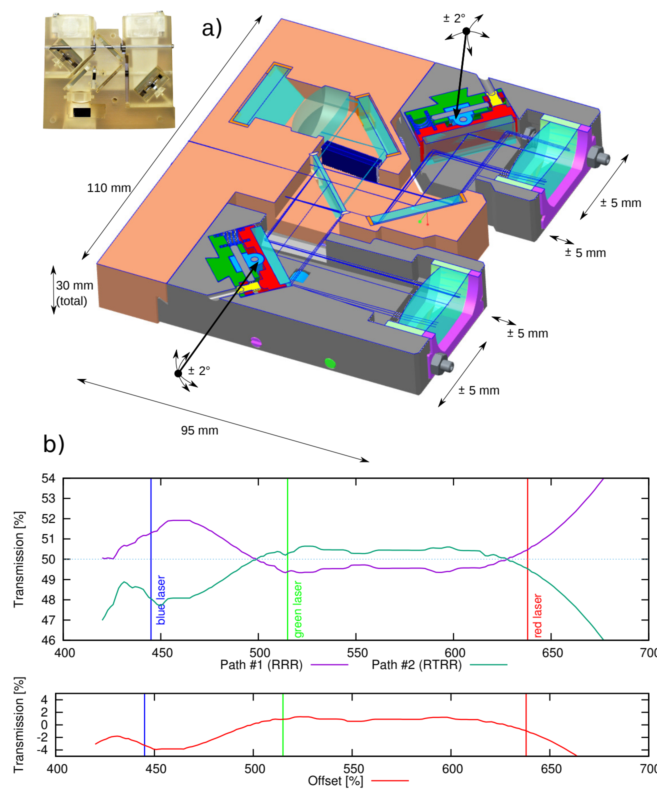


Fig. 2. (a) 3D printed prototype and its cross-section. Degrees of freedom include one translation as well as two rotations per arm. (b) per arm transmission as a function of wavelength. R: reflection, T: transmission.

## III. Description of the Opto-Mechanical System

The 4:3 projected image is split towards each arms with a 50:50 beam-splitter. Fig. 2(b) illustrates the difference in color transmission for each arm. Overall, the laser intensity difference between each image never exceeds 3%, and is not perceptible. Mirrors are used to satisfy the system's

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constraints: the optical path length between $l_1$ and $l_2$ must equal $f_1 + f_2$, both images must be projected from a same height along $\vec{e}_y$, the length of each arm must be adjustable separately. The image is relayed by two plastic plates, easily integrable inside the helmet visor: the required surface on the plate is $\approx$ 2.5 cm$^2$ per eye, and no treatment is required to increase its reflectivity, since the optical intensity of the system is large. The plastic plates are in the same plane, for simplicity and for future integration into the visor. The position of the system inside the helmet, as shown in Fig. 3 requires $g \approx 90$ mm.

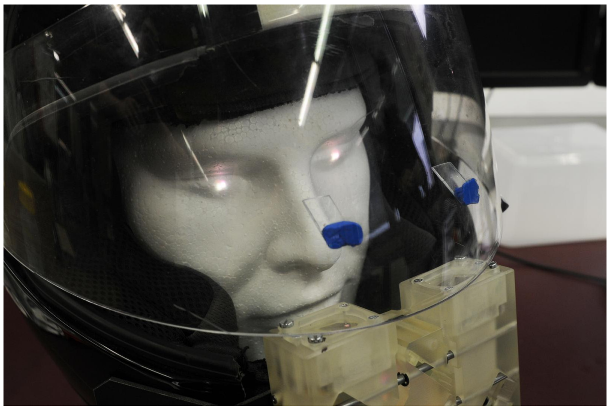

Fig. 3. HMD system mounted in a standard helmet. The filters are removed to illustrate the beam path toward the user eye and the required size of the plastic plates. All shock-absorbing parts are conserved, only the external plastic chin piece was removed.

## IV. Results and Conclusion

The image quality is assessed by comparing the image as seen from inside the helmet with the source image projected onto a wall. Fig. 4(a) shows the virtual image as seen outside on a sunny day, at high luminosity, when a 30 dB neutral density (ND) filter is set after the projector. In Fig. 4(b), the virtual image is seen indoors, with higher attenuation of 34.7 dB. To estimate the virtual image deformation, a picture of the source image $S$ projected onto a wall is compared with the picture $I_o$ of Fig. 4(a). Keypoints in the image $S$ are selected, and are shown in green on Fig. 4(c). Corresponding keypoints are found on image $I_o$, and are superimposed on Fig. 4(c) as black crosses. Minor image deformations can be seen, and originate mainly from the fact that the light beam reaching lenses $A_{1,2}$ does not necessarily coincides with their optical axes, depending on the adjustment of mirrors $M_{1,2}$. A spot diagram of the simulated system is shown in Fig. 4(d), picturing the spot size on the retina for each wavelength of the system. The variation in spot size origins from the 193 nm wavelength difference between the blue and red laser of the projector. Therefore, despite the use of achromatic lenses, different wavelengths focus at slightly different $z$-values.

The projector has a resolution of $N_x \times N_y = 640 \times 480$ pixels, which represents 91 pixels/° horizontally and 96 pixels/° vertically. Both numbers are under the eye resolution limit. Let $i_s = i_2 f_{\text{eye}}/f_2 = 1.04$ mm be the image size on the retina, with $f_{\text{eye}} = 18$ mm. The waist size on the retina is

TABLE I
SPECIFICATION CHART

| | |
|---|---|
| **Image source** | |
| Micro-projector | Lemoptix VGA |
| Resolution | 640 × 480 pixels |
| Wavelengths | 445nm, 515nm, 638nm |
| Input angle | 30° |
| **Display system** | |
| Virtual image distance | Infinity |
| Last-lens – eye distance | 90 mm |
| Field of view | 7°× 5° |
| Angular resolution | > 90 pixels/° |

$2\omega_f = 4\lambda\pi^{-1} f_{\text{eye}} f_1 f_2^{-1} \omega_0^{-1} = 5.6$ µm, with $2\omega_0 = 0.5$ mm the projector waist size. The waist size on the retina is therefore 72% larger than the pixel size $p_s = 2i_s/N_x = 3.3$ µm, and therefore the system resolution is higher than the one perceived by the eye. This is further confirmed by the spot size of Fig. 4(d). The power of the system is of 84 nW per eye, after an attenuation of 34.7 dB with the use of ND filters. Coupled with a software control, the system can adapt to any light conditions.

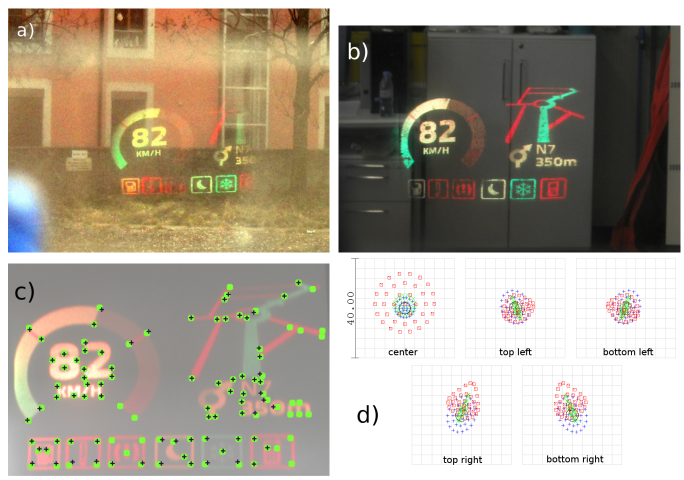


Fig. 4. (a) Picture taken outside, on a sunny day. The filters provide an attenuation of 30 dB. Vignetting comes from the camera; the image is fully visible with human eyes. (b) Picture taken from the helmet, indoors, with an attenuation of 34.7 dB. (c) Image projected onto a wall (green keypoints) compared with the image seen from the helmet (black crosses), corresponding to picture (a). (d) Spot diagram simulated on the retina (scale in µm). Colors corresponds to the three wavelengths: blue 445 nm, green 515 nm, red 638 nm.

In conclusion, we have reported a new design of HMDS suitable for motorcycle users. The binocular system features a good compactness of $\sim 1/3$ of a liter, smoothly fits inside a standard helmet with minimal work, and provides high luminosity for daylight conditions. The system is adjustable via two rotations and one translation per eye, and an additional degree of freedom is provided to adjust the beam convergence in the $\vec{e}_z$ direction. The projected image of a size of 7°×5°, is visible in the bottom of the user FOV, thereby suited for driving conditions.

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