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High Brightness MEMS Mirror Based Head-Up Display (HUD) Modules with Wireless Data Streaming Capability

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ABSTRACT

A high brightness Head-Up Display (HUD) module was demonstrated with a fast, dual-axis MEMS mirror that displays vector images and text, utilizing its ~8kHz bandwidth on both axes. Two methodologies were evaluated: in one, the mirror steers a laser at wide angles of >48° on transparent multi-color fluorescent emissive film and displays content directly on the windshield, and in the other the mirror displays content on reflective multi-color emissive phosphor plates reflected off the windshield to create a virtual image for the driver. The display module is compact, consisting of a single laser diode, off-the-shelf lenses and a MEMS mirror in combination with a MEMS controller to enable precise movement of the mirror's X- and Y-axis. The MEMS controller offers both USB and wireless streaming capability and we utilize a library of functions on a host computer for creating content and controlling the mirror. Integration with smart phone applications is demonstrated, utilizing the mobile device both for content generation based on various messages or data, and for content streaming to the MEMS controller via Bluetooth interface. The display unit is highly resistant to vibrations and shock, and requires only ~1.5W to operate, even with content readable in sunlit outdoor conditions. The low power requirement is in part due to a vector graphics approach, allowing the efficient use of laser power, and also due to the use of a single, relatively high efficiency laser and simple optics.

Keywords: MEMS, MEMS Mirror, Head-Up Display, Vector Graphics Display, Remote Phosphor, Laser Phosphor Display, MEMS Display, Laser Emissive Display

1. INTRODUCTION

Head-up displays (HUDs) were introduced in automobiles by GM in 1988. In the past decade they have been offered by several automakers, although covering only a small niche of the market. They are now available in many high end car models from various manufacturers, as standard or optional features, thanks to significant R&D progress during the last decade. However, in contradiction to various forecasts, HUDs have still not penetrated the automotive market nearly as much as expected [1]. Automotive safety has been stated as the main driving force for implementing HUDs, which are capable of displaying information without requiring the user to take their eyes off the road, e.g. content from night vision cameras, navigation systems, and others. Studies of driving behavior found that improper lookout, inattention and distraction [2], as well as "eyes-off-road durations of greater than two seconds", have significant impact on crash risks [3]. An analysis of rear-end collision avoidance systems concludes that nearly 40% of drivers "appeared to be distracted within five seconds before the crash-imminent alert." [4] Altogether, it has been found that keeping the driver's attention on the road is one of the biggest contributors to avoid accidents. This of course is strongly coupled with the driver's vision being aimed ahead of the vehicle, through the car's windshield.

For future HUD applications, researchers have proposed different scenarios based on advanced environmental recognition technologies to support and alert the user. For example, systems could highlight traffic signs or obstacles on the road, alerting the driver of what to expect ahead in all road conditions. These extended "augmented reality" versions may utilize parts or the whole windshield of the car to cover whole outside scenario. In contrast to "augmented reality", the stated safety increase based on the HUD use is primarily derived from the fact that all necessary information from the dashboard is displayed on the windshield and that it is highly simplified and not overloading the driver [5]. Bringing all strings together leads to the conclusion that an automotive head-up display is intended to project much of the regular information the driver would otherwise get from the dashboard, displayed in a minimalistic and common way to minimize driver distraction. This information may include vehicle speed, gear, radio settings, and navigation information. To enable this, a typical system consists of several function blocks, as illustrated in Figure 1a.

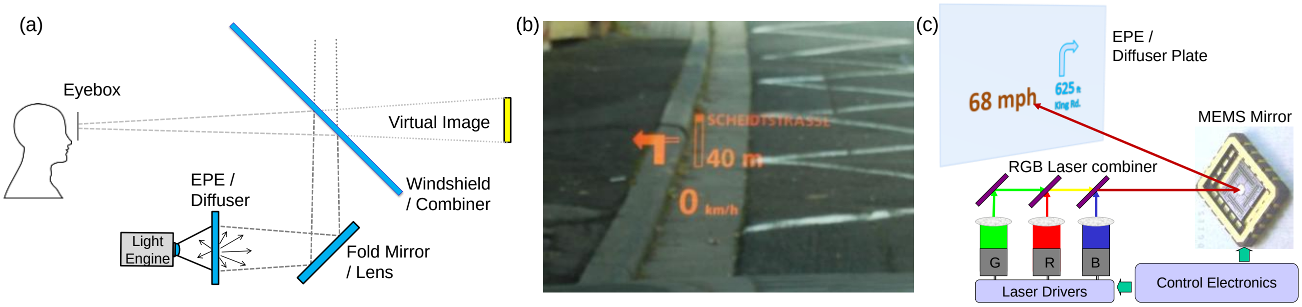

Figure 1. Virtual image HUD: (a) Schematic diagram of the setup where a light engine projects on a diffuser, and the resulting image is reflected by folding optics and a windshield/combiner to the viewer. (b) Simulated image of typical HUD content (c) Schematic diagram of a MEMS picoprojector based light engine with RGB lasers.

A light engine creates the necessary light with a monochrome or multi-color content for the projection. Recently, there has been increased focus on MEMS-based laser-scanning light engines due to their compact size and saturated color content capability [6]. This light is projected onto a screen surface, also termed the exit pupil expander or EPE [6], which is typically a diffuser plate placed at an adequate distance from the projector to achieve needed image size. This screen, typically several centimeters on the diagonal, is actually viewed by the driver due to the alignment of folding mirrors and lenses which make it visible “through” the windshield or a separate combiner plate as depicted in Figure 1a. The optical path between the diffuser plate and the combiner may include a fairly complex set of folding mirrors and aspheric mirrors or lenses to achieve both a larger virtual image size as well as a greater perceived distance between the driver and the virtual image. In existing HUDs, total distance of the virtual image to the driver may be between 1.5m to 2m.

This type of display offers a number of very desirable properties, for example the long focal distance to the image for driver’s additional comfort and the fact that the information is mostly available only to the driver and not viewable by others. On the other hand it is less efficient (electrical power to actual viewable optical brightness) and bears severe challenges which we will briefly outline. Although simplified in the illustration in Figure 1 the image on the diffuser plate has to pass several mirrors and/or lenses, each of which result in some brightness loss. Furthermore, the final reflection from the transparent windshield or combiner plate is low (typically less than 25% reflected), i.e. the image transmitted through the windshield to the area above the vehicle is brighter than the one viewed by the driver. But the real challenges in brightness and inefficiency happen prior to this optical train. RGB lasers have low efficiency, especially green lasers, which limits the maximum brightness of the system. Laser combining optics which form a single laser beam, and MEMS projectors can have a further 50% loss. The diffuser plate can have efficiency below 50%.

Regarding the forming of the image content itself, there is an additional inefficiency. A typical non-distracting HUD image is mostly empty space and a small percent of the available image area contains content. Figure 1b and Figure 1c examples show such images. Due to the various beam retrace considerations in laser raster projection (active video time vs. complete period of one raster) and the small amount of content, lasers are actually utilized only a few percent of the time. Given the upper limitation on power in the RGB lasers (e.g. 50mW for green,) the fact that the laser is turned on for roughly ~5% of the time to form the example images in Figure 1 results in ~10-20 times lower brightness. Finally, it is found that if drivers wear polarized glasses, the display may become invisible because of its strong polarization.

One alternative approach to the “virtual image HUD” described above is a “windshield display”, displaying content directly onto the windshield itself so that it can be viewed by the driver and other passengers. In 2007 we published [7] results of a project for an automotive customer to create a prototype windshield display system which could cover as much windshield area as possible. This concept was enabled by mostly transparent fluorescent emissive “Superimaging” films [8] that were applied to the surface of the windshield or embedded in a windshield. The films contain nano particles which are substantially transparent in visible wavelengths due to their small size, however when illuminated by a 405nm laser beam they emit incoherently and in all directions at longer wavelengths, e.g. in blue or red colors. The result is that the windshield itself has readable content presented on it while otherwise remaining transparent. In this approach all of the optical losses associated with the forming of the virtual image at a distance beyond the windshield are avoided, resulting in superior brightness. Furthermore, the resulting image on the treated windshield is viewable from almost every angle, which removes the restrictive “eye-box” challenge for the drivers.

Regardless of whether the virtual image HUD or windshield display methodology is used, our proposal is to improve the efficiencies and driver feeling by employing a single, efficient laser source, replacing the diffuser plate methodology

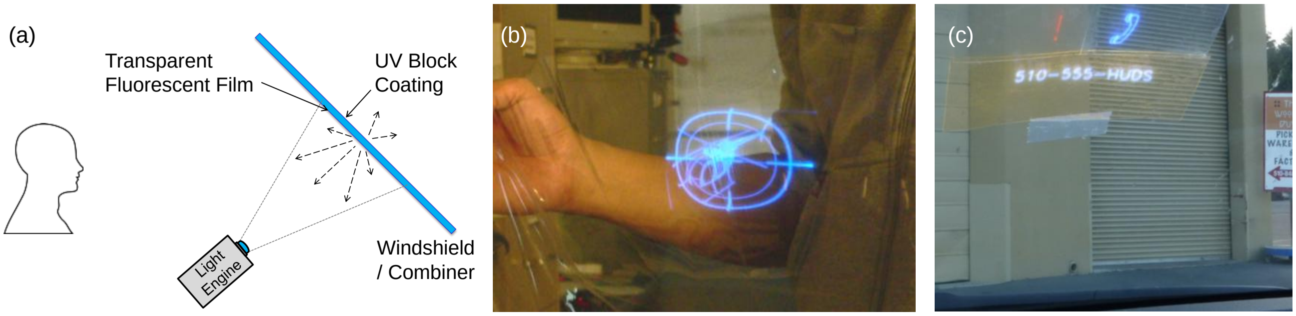

Figure 2. Windshield display [7] using transparent emissive fluorescent film [8]: (a) Schematic diagram of system setup: Light Engine projects (directly) on the windshield/combiner with the film (b) Projection of bitmap content on the blue-emitting film (c) Projection on a windshield completely coated with the film.

with emissive films or remote phosphors, and displaying vector graphics content instead of rastering bitmap images. The key advantages are listed below:

No speckle noise: One of the major problems with laser-based displays is speckle noise [9]. This phenomenon based on interference of the coherent laser light is a significant drawback which trumps many advantages of the laser-based optical sources and therefore a wide variety of methodologies is employed to reduce this effect [9]. The methodologies add design complexity and moving optical parts and while only reducing the problem. In our proposed methodology where images are generated incoherently on emissive materials, speckle noise is virtually non-existent.

No polarization dependence: Unlike laser based picoprojectors or LCDs, the phosphor-emitted images are not polarized and eliminate the dimming issue for users wearing polarized (sun) glasses.

Higher efficiency and lower cost laser sources: Lasers at the 405nm and 445-450nm wavelengths are widely used in blue ray DVDs and other applications and have become widely popular in 3D laser printing systems and many other applications where efficient laser sources are needed at a highly competitive consumer price point. Typical efficiency of a single mode 405nm laser diode with approx. 200mW of output power is 20% (~5V and 200mA). As a comparison, green laser diodes used in picoprojector type HUDs achieve at most 5% and remain very costly.

Less complex optical design: A single (color) laser diode source requires very simple optics without any dichroic mirrors and combiners as used to combine red, green, and blue lasers into a single co-axial beam. RGB lasers are not only difficult to align (especially over automotive temperature range) while reducing optical efficiency, but they are also relatively costly. With a single laser, complex color control hardware and algorithms can also be avoided.

High optical resolution: The laser based display with 405nm wavelength can have a higher optical resolution than an RGB based display, due to the shorter wavelength laser, especially if compared with RGB's red wavelength of ~638nm. In the case of vector graphics this results in increased image sharpness and clarity.

2. MEMS MIRROR AND DRIVER

To achieve a laser-scanning module with a lot of flexibility, we targeted a device design with point-to-point or quasi-static two-axis beam steering capability with significant tip/tilt angle and with a high frequency response bandwidth. We utilized gimbal-less two-axis MEMS beam-steering mirrors based on monolithic, vertical combdrive actuators [10]-[13]. The gimbal-less design results in fastest two-axis beam steering with large optical deflections of >20° over the entire device bandwidth, from DC to several kHz for the chosen 0.8mm diameter mirror size. The capability for equally fast beam steering in both axes is a great match for use in laser tracking, laser marking and 3D printing applications, as well as for displaying of vector graphics as in the present work. As mentioned, we had previously demonstrated a highly adaptive MEMS-based display [7] and its application for windshield HUDs. However, at that time, the MEMS mirrors were limited to actuation in only one quadrant, meaning that under static driving conditions both x-axis and y-axis angle could be actuated from 0° to ~7° of mechanical angle, but not in the opposite direction. Furthermore the MEMS mirror DC response was a square-law function due to the electrostatic nature of the vertical combdrive force. Lastly, device bandwidths were not as high as possible with current designs. In this work we designed a MEMS mirror with bi-directional tilt capability on both axes, therefore addressing four quadrants. This capability is enabled by the fact that each of the four electrostatic rotators allows for bi-directional rotation.

The MEMS mirror device (Figure 3a) is made entirely of monolithic single-crystal silicon, resulting in excellent repeatability and reliability. Flat, smooth mirror surfaces are coated with a thin film of aluminum with high broadband reflectance in the wavelengths suitable for phosphor activation, i.e. 405nm and 445-450nm. Flatness of the final, metalized and packaged mirrors is tested on a WYKO NT3300 interferometer. Most mirrors measure between 7m to 10m radius of curvature. With such high flatness and surface roughness below 5nm, the mirrors are highly suitable for the 405nm laser beam steering application. Another important benefit of electrostatic driving and pure single-crystal silicon construction is an exceptionally wide range of operation temperature. We have demonstrated normal operation at up to 200°C [13] and in other researchers' projects mirrors were used at cryogenic temperatures down to ~4°K [14].

As mentioned above, the design is focused on wide bandwidth to allow the laser beam scan to directly follow arbitrary voltage commands on a point-to-point basis. A fast sequence of actuation voltages results in a fast sequence of angles for point-to-point scanning. There is a one-to-one correspondence of actuation voltages and resulting angles: it is highly repeatable with no detectable degradation over time. For devices with mechanical tilt range of -5° to +5° on each axis, tilt resolution (repeatability of steering to a specific angle over an extended period of time) is within 0.6 milli-degrees or within 10 micro-radians. The desired trajectories must be pre-conditioned in order to limit bandwidth of the waveform reaching the device and to prevent oscillations [7],[11]. This is done firstly by time-domain input shaping of the vector content acceleration/constant velocity/deceleration control during interpolation. Then it is also done in frequency domain by filtering out the content that would excite the high quality factor resonant response seen in Figure 3c. As described in [11], we utilized a digital IIR inverse filter, and increased the bandwidth of the MEMS device to ~8kHz.

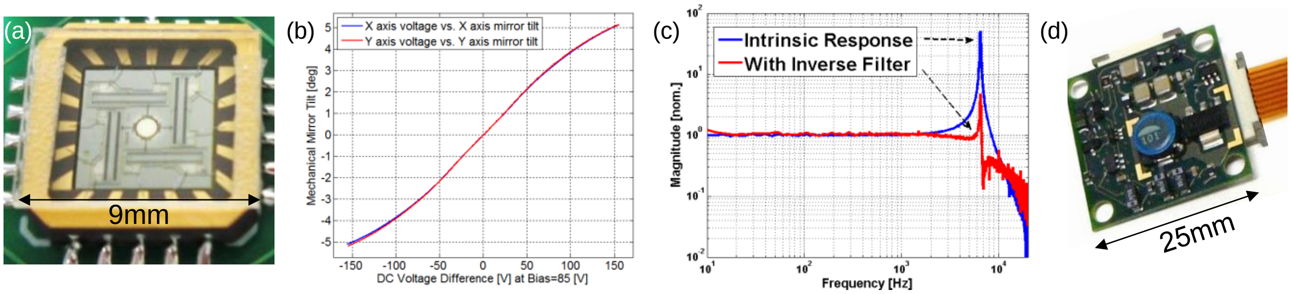

Figure 3. MEMS Mirror Device used in this work: (a) Photograph of the device packaged in a 9mm wide ceramic carrier, (b) Static Voltage Difference vs. Mechanical (X and Y Axis) Angle (c) Intrinsic frequency response with a 6200Hz resonance and frequency response of the device with inverse filtering applied, and (d) 25mm x 25mm form MEMS driver with a 16-bit quad DAC, boost converter, and a high voltage quad-opamp.

To actuate the rotating bi-directional electrostatic combdrives, we utilize a "push-pull" method of driving with a Bias-Differential Quad-channel (BDQ) scheme [12]. This scheme linearizes actuators' voltage-angle relationship as seen in Figure 3b, and improves smooth transitions from one quadrant to another, i.e. from one actuator to another within the device. In this mode both the positive rotation portion and the negative rotation portion of each rotator are always differentially engaged. Specifically, we bias all of the moving sections of the combdrives with 85V with respect to stators. Then, in response to user commands for mirror tilt, one section is given additional voltage and the opposite-acting section reduced voltage. Driving the MEMS mirror to full tip/tilt angles on both axes (4-quadrants) therefore utilizes four high voltage channels with 0 to ~160V output range.

For the prototype setup, a USB MEMS Controller was used which contains a fast MCU, a USB and Bluetooth interface, and an embedded "PicoAmp" MEMS driver. The PicoAmp is a quad-channel 16-bit high voltage driver with SPI digital input and programmable hardware filtering. The MEMS driver has been reduced in size to a (25x25x10)mm^3 volume (Figure 3d). It runs on a +5VDC power supply and ~25mA of current in active state. The USB controller can interface with a host computer through a Windows API (application programming interface), Android API, or by serial terminal commands, either via USB cable or wirelessly via Bluetooth. The MEMS device can be controlled from a host PC, a mobile device, or other development platforms such as Raspberry Pi or Arduino. The USB Controller coupled with the development software has real time content generation and display capability.

3. WIDE-ANGLE VECTOR GRAPHICS DISPLAY METHODOLOGY

Unlike in bitmap raster based displays where the laser beam traces each line of a given display area, in vector graphics displays the laser traces out only the specific path of the displayed vectors, point by point, as in "connect-the-dots" pictures. This display methodology is found in the vast majority of laser entertainment shows and has been demonstrated in windshield displays and HUDs [7],[8],[15]. The major advantages are the significantly lower bandwidth and computation requirement for the beam steering mechanism (mirror) and its controllers/drivers and also approximately an order of magnitude brighter content in the case of simple HUD-type text and signage. Significant disadvantage is a limitation on the quantity and type of content since content can generally only have lines and outlines, and not bold fonts and fills. Vector graphic displays also often have a lower refresh rate due to the bandwidth limitation of the beam steering device. Nevertheless, due to brightness and simplicity advantages we utilized this approach in this work. As for the downsides of vector display, we continue to make improvements in available beam steering bandwidth to achieve higher refresh rates and content complexity. As mentioned in Sec. 2, the MEMS mirror in this work was driven with approximately 8kHz of bandwidth which allows us to display complex content at a 40Hz refresh rate.

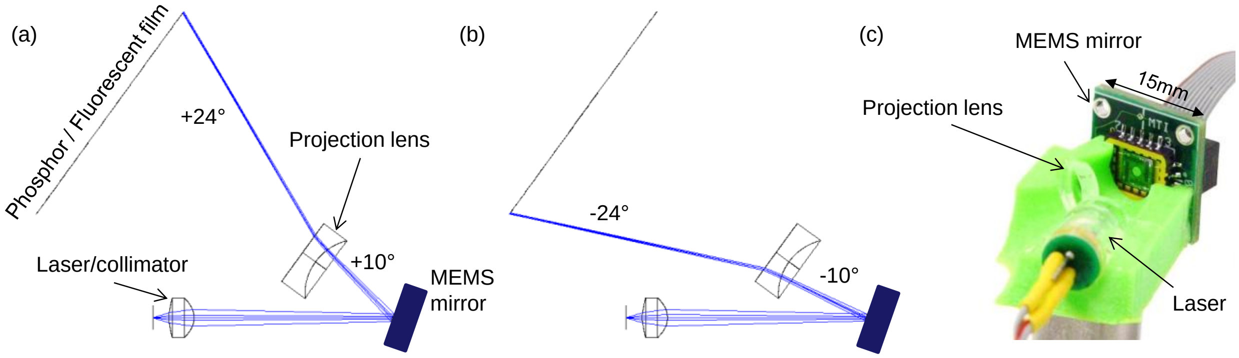

Figure 4. MEMS Scan Module optical cell design: (a,b) Schematic of design for increased field of view scanning. Laser diode is collimated and the beam is then reduced by a convex-concave lens beam reducer. MEMS mirror is placed between the beam reducer lenses, scanning the beam over the concave lens which increases the scanning angle and re-collimates the beam. (c) Prototype MEMS Scan Module with off the shelf optics and a printed plastic mount.

In order to address a wide area of the windshield from a short distance on the dashboard for the windshield display, as well as to reduce the size of the virtual image HUD, it is useful to increase the field of view of the MEMS light engine. Since the optical scanning angle of our MEMS mirror is -10° to +10°, we employed a wide angle lens design similar to the one previously described [7] to increase the overall field of view to over 48°. In this improved methodology we reduced the number of optical elements by inserting the MEMS mirror into the middle of the wide angle objective lens set. Namely as seen in Figure 4, the MEMS mirror is placed in between the positive lens element and the negative lens element which together form the beam-reducer that increases the scan angle by approximately 2.4X. Finally, the complete optical cell can be reduced in size and formed out of simple spherical off-the-shelf lens elements as seen in Figure 4c, and held in place by a machined or 3D printed cell housing.

The 48° scanning capability comes with inherent pin-cushion distortion. In addition to that, any misalignment of the optics and the MEMS mirror as well as some F-Theta nonlinearity results in a non-ideal scan field of the light engine. As we see from the device's static response in Figure 3b, there is nonlinearity at larger angles in the device as well adding to the complexity of the final relationship between input commands and output beam location. Here we find another major advantage of vector graphics methodology, namely that it allows us to practically eliminate all of these distortions by allowing the user to fully control the beam position and velocity and therefore to correct any amount of optical field distortion either computationally by model or by actual measurement/calibration [7]. We have successfully demonstrated correction of major non-linearities in the projection lens, MEMS device, as well as correction of perspective angles when projecting content onto non-normal surfaces in the past, and have integrated these correction capabilities into our light engine control software. Ultimately, a complete unit-specific look up table can be created during production/calibration that fully eliminates beam pointing errors.

Prototype content is generated on a host PC in MirrorcleDraw software which allows the user to draw arbitrary freehand or line sketches and compose various parametric mathematical curves. It is also possible to input text or to load multi-frame animations consisting of lists of keypoints for each frame. The raw path data is then interpolated to the system's sample rate in a way that maximizes the laser on time, resulting in 80%-85% usage of available laser power. Lastly the software applies digital filtering to the sample content to optimize the driving voltages for the device's dynamics.

4. VIRTUAL IMAGE HEAD-UP DISPLAYS BASED ON EMMISSIVE FILM

We designed a simple testing setup which allowed us to experiment with different methods of mounting the MEMS scan module with respect to the optics, with different emissive and phosphor films, varying optical magnifications, and other aspects. As seen in Figure 5 we also made an optical model to represent the prototype setup. In the Figure 5a version, the fluorescent emissive film obtained from Sun Innovations is back-illuminated and the emission on the opposite side is viewed by the driver. This is possible because the film is transparent to visible wavelengths and can therefore be illuminated from any side with the 405nm laser. In the Figure 5b version we illuminate the film from the same side that is viewed by the driver. In this, reflective option we mount the fluorescent film directly on an aluminum mirror. The emission from the film in visible wavelengths was therefore reflected, nearly doubling the emitted brightness available to the viewer. This option was also tested with phosphor plate obtained from PhosphorTech Corporation.

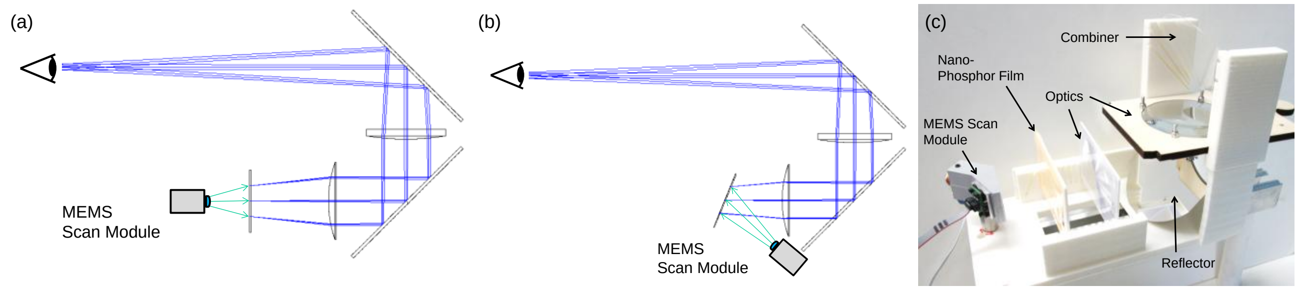

Figure 5. Testing setup for the virtual image HUD with emissive film: (a) simplified optical model of the transmissive version using the transparent fluorescent emissive film. (b) optical model of the reflective version in which the film or phosphor plates were used, and backed by an aluminum mirror for increased brightness. (c) Actual testing setup with flexible construction for easy modification of optical gain etc.

Initial experimentation was focused on monochrome displays. We experimented with displaying a variety of content on emissive films and phosphor plates which emit in various wavelengths. By far the highest brightness and visibility was obtained with samples that emit white light. Figure 6a,b images show a comparison of some sample content projected to the transparent film and a phosphor plate, respectively. Content is projected with a 40Hz refresh rate and emission is mostly white. We then experimented with brightness increase by aluminum-mirror backing. We applied the film smoothly onto the mirror surface with no air-gap and obtained excellent results in what was perceived as doubling of brightness and no reduction in clarity or quality. The image in Figure 6c attempts to show the comparison although it was difficult to capture by camera. The left word “HUD” is projected from a transparent film with no mirror and the right “HUD” from a film applied over the mirror.

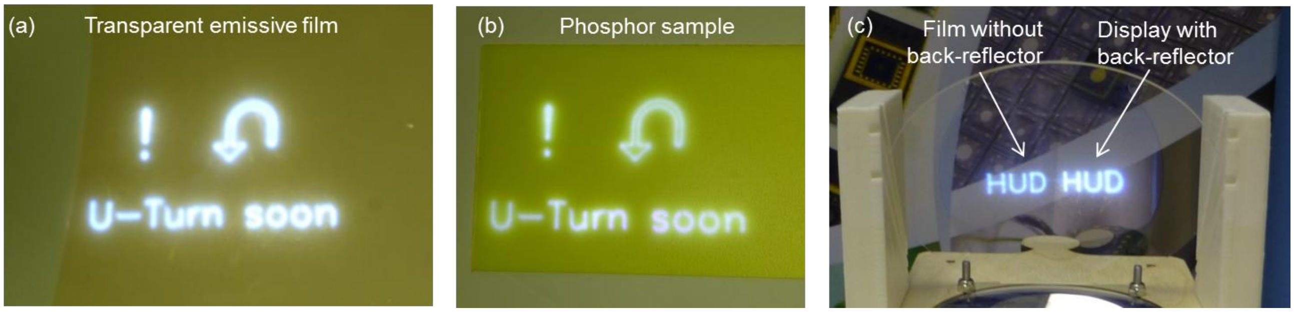

Figure 6. Examples of monochrome vector content displayed on emissive films, excited by 405nm laser wavelength.

To create multi-color content we prepared several emissive plates with combinations of films with different emitting wavelength. The concept we explored is that HUDs often have content in different colors in separate areas of the display as different colors apply to different types of messages to the driver. In our prototype we applied a red-emitting film to the top left corner of the plate for warnings to the driver (Figure 7a), a blue-emitting film to the top right corner for indicators such as driving directions, and a white-emitting film to the bottom half of the plate for speed and text messages. Each film section was applied to the aluminum mirror as seen in Figure 7b and the 405nm scanning laser resulted in a 3-color HUD image which feels more comfortable and informative to the viewer. We included this plate in the reflective-version prototype and took the unit to sunlit outdoors conditions and noted good readability (Figure 7c).

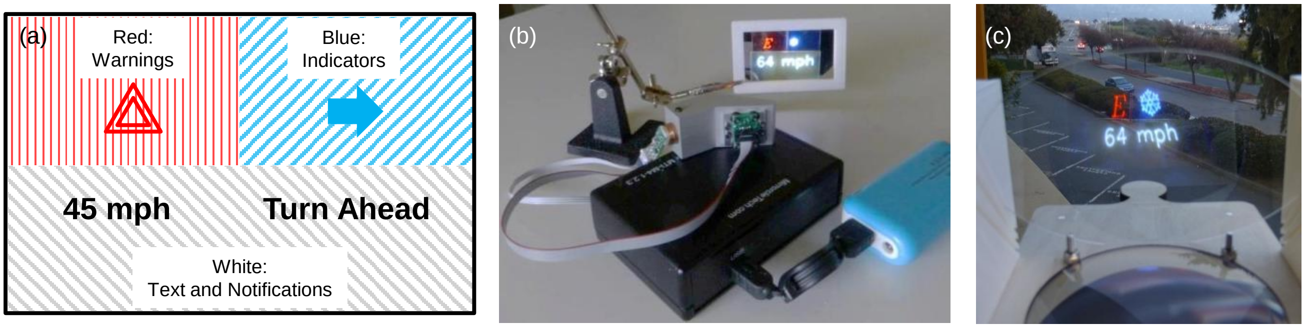

Figure 7. Displaying multi-color content with a 405nm laser and a segmented emissive film screen: (a) proposal to segment the HUD display into sections of different color to convey more information to driver, (b) a demonstration of concept with a battery powered MEMS mirror scan module illuminating 3 color content on a mirror-backed emissive film plate. (c) outdoor demonstration of the same plate after it is inserted in our virtual image HUD prototype as the EPE.

As a future extension of this work, we are investigating the use of stripe-patterned phosphor plates to achieve full color bitmap images and video using a raster scanning methodology. Using patterned multi-color phosphors to create color video as seen in [16],[17] and in products of Prysm Inc., and applying them to HUDs as seen in this work would be a great technological alternative to present light engines and would offer most of the advantages proposed here.

5. MOBILE DEVICE BASED CONTENT AND CAPABILITIES – THE PLAYZER HUD

Automotive manufacturers are understandably restrictive and conservative in the introduction of new technologies and products. Furthermore, once new technologies are introduced they often lack flexible interfacing with drivers own electronics and smartphones which are developing at a remarkably fast pace. In an after-market environment users are attracted to useful or “cool” new solutions and prefer to have them as flexibly integrated with their personal electronics as possible. Some providers such as by e.g. Garmin HUD and HUDWAY Apps offer smartphone applications to use Smartphone screens as quasi-HUDs to show directions for navigation, indicating calls, caller IDs or providing any desired short information. Integration of your personal Smartphone into a HUD image can increase safety. However the phone’s display itself is not well suited to the task.

Toward the goal of creating a flexible technology platform which can be utilized in HUDs, we have been developing a compact, battery powered, wirelessly controlled and versatile laser display platform we call the Playzer. The electronics are based on the existing USB-SL controller which is in this case miniaturized and with reduced functionality focused specifically on versatile mobile laser displays. The Playzer unit has a Bluetooth transceiver allowing the smartphone to stream display content at ~1MBaud rate which is fully adequate for multi-color vector graphics as proposed here. An Android/Java-based API is available for developing Apps to display content such as incoming texts, telephone numbers, various pictograms for warnings and navigation. Apps can make use of all Smartphone functionalities which include useful features and data for drivers. The system is fully flexible and supports developers with programming guides and sophisticated examples.

Figure 8. Playzer prototype showing mobile content examples, (a) Displaying a freehand drawing. (b) Displaying current time (c) Smartphone device connected to our virtual image HUD prototype creates and streams text content.

6. CONCLUSIONS

We proposed and demonstrated two alternative concepts for higher brightness head-up displays in cars. They are directly applicable to any similar displays in human field of view such as in helmets, aircraft, ships or e.g. retail store windows. Both the virtual image HUD and the direct windshield display embodiment of the concept are focused on eliminating the need for costly, low optical power, and inefficient RGB laser modules. We demonstrated that higher power and higher efficiency 405nm lasers are able to display multi-color content with high brightness, no speckle noise and no polarization sensitivity by facilitating emissive films and phosphor plates. The demonstrations and prototypes were very rudimentary and not attempting to simulate the complexity the optics of a real product. Yet, even in its simple form they were able to perform, battery powered, while driving a car in bright sunlight outdoor conditions. Lastly, we showed that a simple mobile device application in conjunction with after-market hardware could be utilized to achieve a high quality HUD.

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