Presented at SPIE Conference on MOEMS and Miniaturized Systems, San Francisco, CA, Feb 3rd, 2019

MEMS Mirror Module for Programmable Light System

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ABSTRACT

An updated Programmable Light System (PLS) is demonstrated using a MEMS Mirror Module (MMM), allowing users to program the brightness and shape of a projected white light in a variety of dynamic solid-state lighting applications, e.g. in automotive dynamic headlights. The MMM is a new module which consists of a fast beam steering MEMS mirror with high optical laser power handling and a smart MEMS Driver with real time monitoring of the MEMS mirror for better system safety and mirror control. The PLS consists of the MMM, a multi-Watt 445-450nm laser source with beam shaping optics, a phosphor target, and projection optics to project a white light within the field of view of up to 60°. Devices such as the 1.2mm diameter A3I12.2 and 2.0mm diameter A7M20.1 aluminum coated mirror have been tested at >8W of CW power before seeing any damage to the device. The A7M20.1 MEMS mirror has been extensively tested (>100 hours) with 4W of CW power at room temperature with no physical damage. Same 4W operation, has also been successfully tested at elevated environmental temperature of 100°C during extended tests.

PLS prototypes to date utilize only ~1W-2W laser diode sources, as limited by power of available laser diodes. The extended tests and thermal studies of the MMM however show that operation at up to 100°C with e.g. 4W CW power could be safely run for at least 10000 hours, even with MEMS mirrors with a simple aluminum coating (no protection or enhancement layers).

Keywords: MEMS Mirror, Beam Steering Mirror, Solid State Lighting, Phosphor Lighting, Programmable Light System, White Light Scanner, Automotive Display, Dynamic Headlight Projector, MEMS LiDAR

1. INTRODUCTION

1.1 SOLID STATE LIGHTING APPLICATIONS

As automotive standards and technologies improve and as features once only available in luxury models start becoming available in standard models, auto manufacturers are constantly on the lookout for new technologies they can incorporate into future car designs. Technologies such as parking assist, LED lighting, and autonomous driving are becoming more common in standard models, and many car designs are converging in shape and features to achieve the best mileage and comfort for their customers. Manufacturers are now looking towards innovative technologies that can best assist drivers and allow them to individualize their own cars with custom branding and personalization [1]. Commercial, industrial, and public automotive manufacturers are investigating solutions to increase safety and the quality of their customers' experiences. Recent developments in lighting applications enable the driver to illuminate various features on the road and project custom "courtesy light" content to greet the driver. Programmable laser projectors would allow users to efficiently illuminate arbitrary locations, draw custom graphics, and display custom, individualized content (Figure 1). This "programmable lighting" would allow the manufacturers as well as consumers to have a level of interaction and personalization that was previously not feasible or affordable.

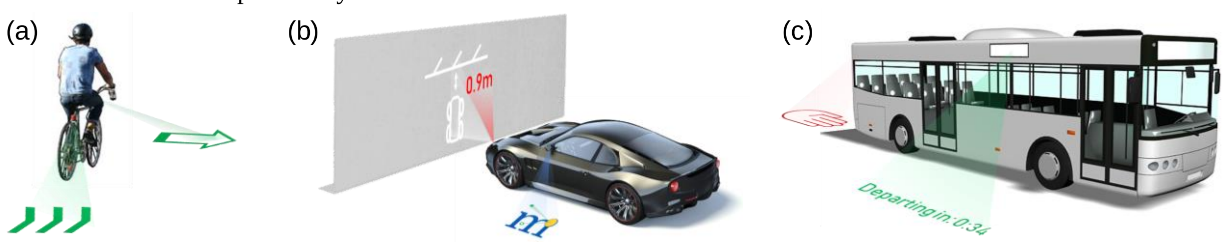

Figure 1. (a) Battery powered laser projection system used as indicator and warning lights on a bicycle, (b) multiple laser and white light projectors on a car displaying custom branding and visually conveying information to the driver while parking the car, (c) vector graphics of public transportation schedules, route information, and warnings for frequent stops can all be projected on the ground along with LED displays to make them more effective.

Lighting systems have been advancing from using fluorescent and incandescent bulbs to LED and laser technology [2][3]. Today's LED lighting technology uses blue LED sources to illuminate remote phosphor targets and efficiently create white light based on the combination of phosphor emission and the blue source. The white light is then shaped and projected out using different "secondary" optical elements. In the case of laser-based lighting applications, the LED is replaced with a 450nm laser source, while the remaining system can remain principally the same [4][5]. Lasers are somewhat less efficient than LEDs, however they have distinct advantages which make them attractive to lighting designers. Namely, the smaller illumination source allows for more compact lighting designs [6], especially with respect to the secondary (projection) optics. Smaller illumination source (hence much higher luminance) also allows for better control of the shape of light being generated [7], e.g. lower divergence for beams that can project 100s of meters in front of the car. The inclusion of lasers as a source in lighting additionally enables dynamic lighting functions where light can be directed and concentrated to certain areas or scanned over the entire Field of View (FoV) by using scanning MEMS mirror technology [8][9].

1.2 MEMS MIRROR BASED DISPLAY AND LIGHTING

Laser beam steering technology has been available for decades in the form of galvanometer scanners ("galvos"), but they are large in size, consume significant electrical power, and have limited lifetimes; thus, they have not been considered in the emerging automotive focus on laser technologies beyond early prototypes. The beam steering technology of choice has been narrowed down for both the LiDAR technology needs and lighting technology needs to MEMS mirrors. Namely, MEMS mirror based optical engines can be highly compact and in some (electrostatic) designs could qualify for extreme automotive (temperature) environments. Various types of MEMS mirrors exist – such as piezo-electric MEMS mirrors [10], magnet and current based MEMS mirrors [11], and electro-static combdrive based MEMS mirrors [12]. Piezo-electric MEMS mirrors have low operating voltage and can operate in analog, point-to-point beam steering, but typically have drift, hysteresis and limited repeatability and reliability due to the nature of the piezo-resistive structural materials, especially over temperature. Magnetic or current-based MEMS mirrors typically require high power to be driven and have a narrow operating temperature range, thus limiting their application use cases. Although current-based driving can seem attractive due to the simplicity of low-voltage electronics, passing substantial currents through microscopic structural mechanical elements of a moving structure inherently limits reliability, creates heat, and consumes significant power.

Combfinger-based electrostatic MEMS mirrors do not have any of the above limitations. While they require high voltage to achieve adequate forces and torques, the power consumption remains very low, with the MEMS mirror consuming less than 1mW even when driven in the most aggressive manner. The required high voltage is generated efficiently by miniature low-power electronics in practically a 10mm x 10mm PCB area. Most importantly, the electrostatic effect of attraction of two plates under a voltage difference essentially has no temperature limitations - the operation is based on silicon beams and air. Our gimbal-less dual-axis MEMS mirrors have been successfully used from 1°K to 470°K.

MEMS mirror designs also vary by operating or beam-steering modes: quasi-static or "point-to-point" designs allow the mirror to steer a laser beam to any arbitrary position and at arbitrary velocity while "resonant mode" designs allow the mirror only sinusoidal continuous motion at a single frequency, albeit at fast frequencies of >10kHz.

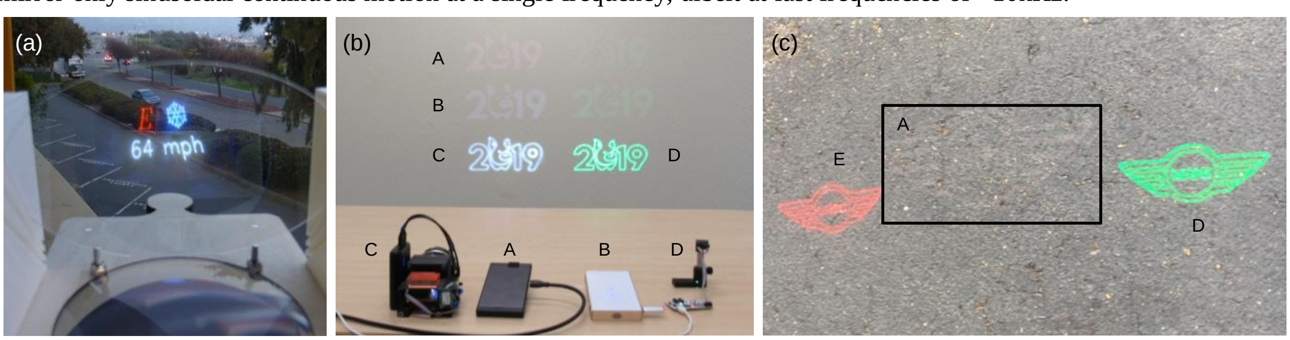

Figure 2. (a) example of a Head-Up-Display using a 405nm laser based Scan Module illuminating a phosphor target with different color regions, (b) An indoor comparison of multiple projection technologies at 2m distance: A: 32 Lumen Scanning MEMS PicoProjector, B: 100 Lumen DLP-based Mini Projector, C: ~6 Lumen PLS, D: ~5 Lumen green Playzer, E: ~5 Lumen red Playzer, (c) outdoor/cloudy daytime comparison of A, D and E projected onto road from 1m height.

Typical scanners used in projection display applications use resonant scanning for the fast axis, and quasi-static scanning for the slow axis. This allows designers to create video rate projectors (e.g. >50000 lines/s). However, quasi-static beam scanning has the distinct advantage of controlling the exact display area. By programmably scanning the laser beam exactly over the vector trace to be displayed, safe laser sources can generate high contrast images that are visible in the day time

(Figure 2a). When the same content is displayed using a video (raster) projector, most of the projector's available brightness is not utilizable and the result is barely visible display content in indoor environment (Figure 2a) and practically invisible content on a road surface outdoor (Figure 2b). Figure 2b shows indoor comparison of various miniature projection technologies at a 2m distance from a wall: an off-the-shelf 32 Lumen scanning mirror based pico-projector, an off-the-shelf 100 Lumen DLP-based mini-projector, a ~5 Lumen Programable Light System (described in this work), and a ~5 Lumen (green, monochrome) Playzer (described in this work). Despite the greater luminous flux (lx) of the pico-projector and the DLP-based mini-projector, the actual measured illuminance at a 2-meter distance in indoor conditions of these projectors was significantly less than that of the PLS and Playzer projectors. The pico-projector and the mini-projector's measured contrast (against background) was 45 lx and 55 lx, respectively. PLS and the green-laser based Playzer measured 595 lx and 755 lx above the background. This difference in illuminance contrast results in the significant brightness and contrast disparity seen in Figure 2b. Figure 2c shows similar comparison outdoors at a 1m distance simulating an automotive courtesy light display where only the Playzer vector projectors are visible.

Gimbal-less dual-axis MEMS mirrors [11]-[15] are unique in qualifying with all the necessary requirements that ultimately enable the applications. They achieve both the low power requirement as well as a wide operating temperature range from -40°C to +125°C. They have a pure silicon construction (no magnets, coils) and the thin light structures can withstand vibrations and shocks of the automotive environment. Such characteristics make them ideal candidates for beam steering in above named commercial and automotive applications. But in order to get the most out of this display technology, a complete technical stack of software, firmware, and hardware solutions are needed. This is detailed in the next section.

2. THE VECTOR GRAPHICS LASER PROJECTION (VGLP) ARCHITECTURE

Our Vector Graphics Laser Projection (VGLP) Architecture combines a full technology stack (Figure 3a) of software, electronics, and optical laser beam-steering solutions to enable the fully-programmable and re-configurable laser projection and display of bright, high-contrast graphic content on a variety of surfaces. The architecture optimizes the performance of lasers and fast dual-axis MEMS mirrors to achieve highest "wall-plug power to visibility" efficiency. Namely, as mentioned above, the critical feature of the architecture is to utilize lasers of modest optical power at very high duty cycles and to deliver all available illumination to the desired vector graphics and image, and not to spread it over a wide area as in typical pico-projectors or DLP displays.

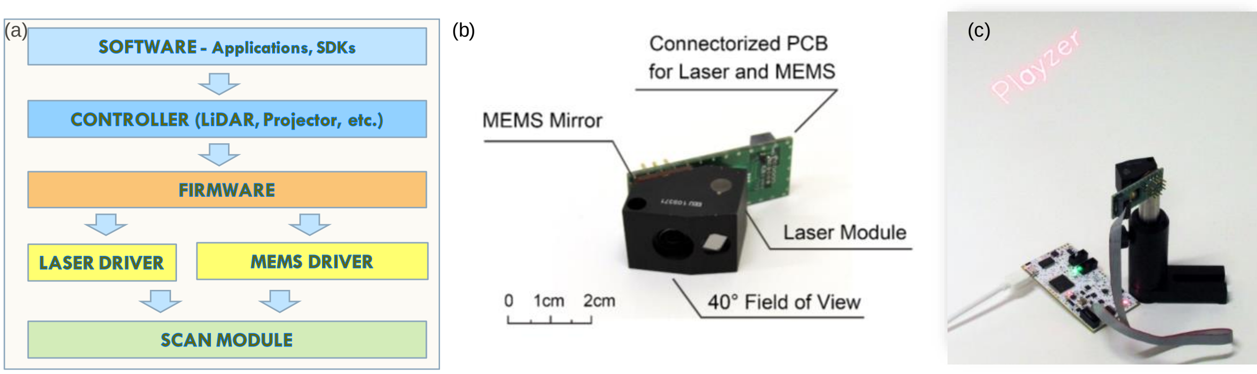

Figure 3. (a) VGLP Architecture technical stack, starting with the Scan Module, going all the way to the top with system level hardware, firmware and software, (b) Scan Module "EaZy 2.0" which integrates a MEMS mirror, laser and optics, (c) Scan Module and OCCIE MEMS Controller form a Playzer Module (open box version), projecting vector graphic content.

2.1 "PLAYZER" VECTOR GRAPHICS LASER PROJECTORS

The above described architecture is implemented in the Playzer – a pocket-sized programmable vector graphic laser projector (Figure 3c, Figure 4). This implementation consists of a MEMS mirror-based Scan Module, Controller electronics, software API, and applications (presently Windows, Linux, or Android-based). This system provides a compact solution for displaying graphics in a multitude of environments, both outdoor and indoor. Furthermore, it allows vector content to be displayed on any kind of surface. These can include residential or commercial walls, road surface, garage walls or doors, parts of the vehicle itself, or even its windows (when associated with fluorescent coating). For the best quality images, the Playzer produces high fidelity scans with a fast-moving dual-axis MEMS mirror (Figure 4a-c). Monochrome Playzers are implemented with one of four laser colors, from Red, Green, Blue or Violet. Full-color (RGB) Playzers include three lasers and a 3-channel 8-bit laser driver. The Playzer's approach to displaying vector graphics is a

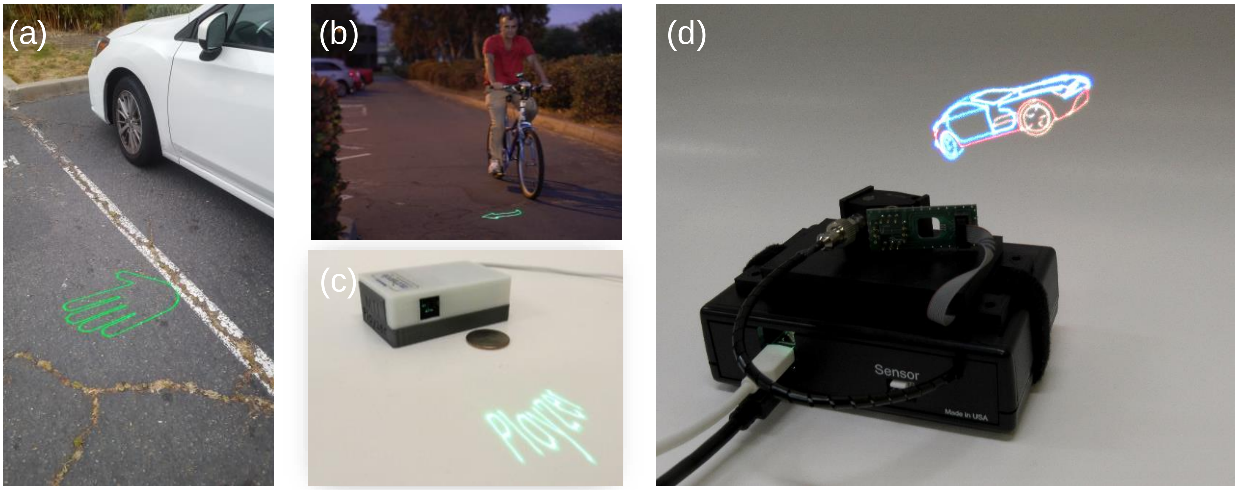

Figure 4. (a) The PZ-02G Green Playzer Module displaying vector graphics in outdoor daytime conditions, (b) a battery powered PZ-01G (green) Playzer Module displaying direction signals, (c) a boxed Playzer (PZ-02G) displaying vector text, showcasing the compact size of the boxed version, and the large FoV, (d) a Full Color RGB Playzer system displaying a vector graphic image of a car using multiple colors.

dual-axis point-to-point (quasistatic) scan, utilizing the bandwidth of the MEMS mirror and maximizing the brightness of the content being displayed. These vector graphics content ("glyphs") have the lowest intrusion and attention requirement from viewers and are a particularly good match for automotive uses - especially in active driving cases. The beam traces only the glyph's paths, with the laser remaining in the on state >85% of the time, and shutting to the off state only between vector segments. The filtering and interpolation algorithms take this into consideration by moving the MEMS mirror faster in the off-sections to reduce the time the laser remains off, and at the same time maintaining uniform velocity along the on-sections to keep uniform laser brightness. At points along the vector graphic where the MEMS mirror slows down to change direction, the laser driver compensates for the undesired change in brightness. The Smart MEMS Driver can additionally monitor the MEMS mirror position and temperature for increased safety.

2.2 SCAN MODULE

A Scan Module (Figure 3b,c) integrates a gimbal-less dual-axis MEMS mirror with a laser source(s), beam shaping, and wide-angle projection (scanning) optics in a compact machined housing for a variety of beam steering applications. Scan Modules are designed to be modular, such that the laser source, MEMS mirror, and the optics can be modified to fit the particular application – such as using visible lasers for any vector graphics display, blue / UV lasers for phosphor-based displays, or IR laser sources for tracking, imaging and 3D sensing applications. While standard Scan Modules provide a 40° field of regard (FoR) for both axes, designs with 100° have been demonstrated for windshield displays (HUDs) and with 130° FoR for LiDAR. Most basic Scan Modules are manufactured with single laser diode source (single wavelength) which is controlled by simple 1-bit digital control or with an 8-bit laser driver. Anodized aluminum housing with an athermalized mechanical design is utilized and several standard designs has been brought to serial production status at a major Contract Manufacturer (e.g. EaZy 2.0, Figure 3b). In addition to the single-color Scan Modules, we have also developed full color (RGB) Scan Modules. In that case, 8-bit laser drivers are employed for each channel to provide for full color laser projection (Figure 4d). The modules are typically assembled with single-mode laser sources to reduce the laser beam size to fit onto the smallest and fastest MEMS mirrors, but in applications such as laser marking and phosphor displays, higher power laser modules (1W, 450nm) with 8-bit laser drivers have also been demonstrated. Using laser collimation and beam shaping, the laser is able to fit on this small mirror, allowing the image to be crisp and clean.

In the case of phosphor displays, the Scan Module's laser is replaced with a high power, multi-mode 445nm-450nm wavelength laser diode, and the optics are modified to have the beam focused at a nearby plane where the phosphor target is mounted. Breadboard-based version and an early Scan Module-based projection system in was demonstrated previously in 2015 [14]. Further improvements have been made to the Dynamic Solid-State Lighting system since 2015 by increasing the laser power, reducing the size of the Scan Module and improving its optical output, and refining the Controller design and reducing its size. This new Scan Module named EaZy 2.0-B1W (Figure 5) includes a 1.2mm diameter A3I12.2-1200AL MEMS mirror with a heatsink package, a 1.6W 445nm laser, beam collimating and shaping optics, and a wide-angle lens to provide the standard 40° field of regard (FoR). The output beam is focused at a ~27mm distance from the output lens. Copper heat sinks are attached above and below the Scan Module's aluminum body to adequately cool the laser source in the Scan Module. The module includes a single 10-pin header to drive the MEMS mirror and the laser. The new high-powered laser Scan Module is now manufactured in a serial production line. It can be used for various applications beside laser-phosphor based lighting. This includes laser marking or processing. Using an Android application via Bluetooth interface, the user can mark surfaces with a stroke of their finger. Figure 5 shows some use cases for this module outside of the PLS. Figure 5a shows displaying of blue vector graphics practically in mid-air due to major air particulate pollution during the tragic events of the Camp Fire in Nov. 2018. To demonstrate the focus and beam steering of the MEMS Mirror Module, our team utilized one module at a recent ribbon-cutting ceremony to cut open the entrance to a new production facility [19], as shown in Figure 5b. The same Scan Module is also demonstrated in Figure 5c, performing laser marking using vector graphics to deliver the maximum laser power to every pixel and mark the content efficiently in time. The Scan Module is enclosed in a blue laser eye-safe housing, and scans onto a paper target approximately 10cm away, laser marking an area of up to 7cm x 7cm (40° FoV). Testing and advancing the Scan Module continues, to further increase efficiency and output power, and heat removal from the laser diode.

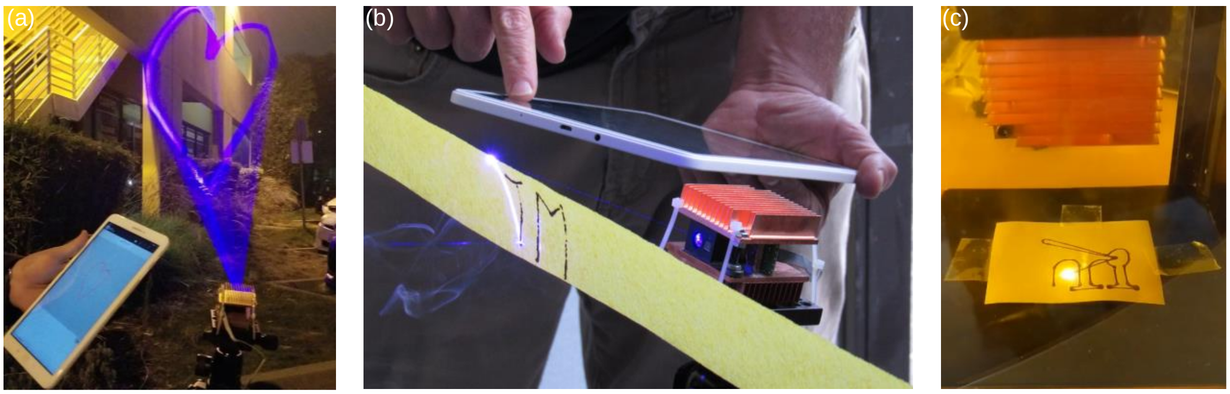

Figure 5. Examples of EaZy 2.0-B1W Scan Module Implementations: (a) Projecting a 0.5W beam with vector graphics in smoky air ~10m away. The user is controlling the projection with an Android tablet, communicating with the MEMS controller over Bluetooth, (b) Cutting a ribbon for Mirrorcle new facility opening in November 2018, (c) Laser marking in an eye-safe housing, using the same MEMS controller and MirrorcleDraw software to draw various vector graphic shapes to mark paper.

2.3 ELECTRONICS – HARDWARE AND FIRMWARE

A subsystem that is responsible for control and communication with the software layer, and that drives the MEMS mirror and lasers is the MEMS controller. The standard USB MEMS Controller “USB-SL MZ” in Fig. 4d, and the compact MEMS Controller nicknamed “OCCIE” in Fig. 3c are both based on Microchip’s PIC32MZ MCU. Controllers include correlated digital outputs, a synchronization port, an integrated 16-bit 4-channel MEMS Driver, and 12-bit 3-channel ADCs for monitoring and real-time control applications. The MEMS Driver itself is a very compact part of the Controller, consuming less than 100mW [16]. The whole Controller can be powered via USB and communicate via USB, Bluetooth, CAN, or Wi-Fi, depending on the specific application configuration.

The controller’s firmware has a generalized proprietary architecture which allows for many methods of controlling the system. There is a variety of commands to set and control the sample rate, onboard filters, refresh rate (frame rate), offsets, scale, rotations, etc. The fundamental paradigm in the lighting applications is to provide the Controller with pre-computed waveforms/content which the projector should output, and then to set the Controller to run that stored content until new content is provided. Ping-pong buffering allows or seamless streaming of new content while existing content continues to display at flicker-less refresh rates (e.g. 60Hz). The correlated digital outputs connect to the 8-bit laser driver, so the Controller can update the MEMS mirror position and laser brightness at each sample outputted at the defined sample rate. The MCU includes flash memory to pre-store content that can display immediately after booting, providing stand-alone display functionality. Wireless connectivity via Bluetooth enables the user to communicate and control from Android-based devices (Figure 5a, 5b).

Qualification of the Controller design and manufacturing for industrial and automotive sector is ongoing.

2.4 SOFTWARE

The MEMS Controller’s firmware communicates with an extensive, multi-platform application programming interface (API) designed primarily within the framework of the VGLP Architecture. Software serves a critical role in the architecture respective to its position at the top of the technical stack: it must interface with the user with his or her target output and facilitate the conversion of general “signage” inputs to an optimized vector graphics scan. Thus, the API is implemented into an interactive and dynamic platform and is made as flexible as possible on allowing a variety of ways to import signage content from third party software, scripts, ILDA files, etc.

As depicted in Figure 6c, the starting point of the displaying process is the digital signage (image, symbol, graphic) which the user wishes to project. This image must be recreated as a vector graphic in one of many available applications: it can be converted from a bitmap image to an outline vector graphic, or it can be directly created in one of our software applications as a full-color vector graphic. To fully define such a vector graphic, we must define all of the vector "keypoints" (X-coordinates, Y-coordinates, and color of the segment to follow) as well as time parameters such as the refresh rate (frame rate) in Hz, and sample rate (actual DAC samples for Controller output). This fully defined keypoint construct is termed a "glyph", and can be efficiently stored in the Controller's RAM or Flash memory. In one implementation for automotive uses, many such pre-created glyphs are stored in the Controller's Flash and can be evoked by the system with simple commands. The remaining flow of data is then from a pre-defined glyph to a fully interpolated list of points that the mirror and laser must follow over a prescribed period of time. The interpolation process, which determines the exact sequence of points to be visited as well as all velocities, accelerations, and decelerations of the beam, can be quite complex if it tries to optimize the waveform to maximally utilize the available bandwidth of a specific MEMS mirror. Ideally the final waveform is such that it minimally sacrifices the details and fidelity of the glyph/image, and at the same time does not excite overshoot and resonance of the MEMS mirror. This waveform (list of samples) passes through linear transforms that allow for adjustment of any scale, offset, and rotation about any axis. Additionally, transforms for projection angle (perspective) can be applied which allow the projector to be aimed at almost any angle with respect to the target surface (e.g. headlight aiming at a grazing angle to the road). In some cases, the sample waveform also undergoes nonlinear transforms that correct nonlinearities added by wide angle optics or other system imperfections [15]. The flexibility of the vector graphics laser projection architecture allows for all types of transforms and corrections (e.g. Look-Up Tables) to be performed on the data as the hardware system fundamentally allows for control of laser beam position and velocity/time, and therefore is fully flexible to be programmed arbitrarily in any region of the field of regard.

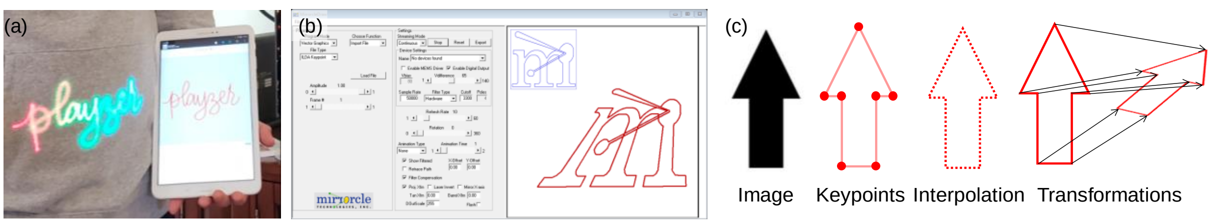

Figure 6. (a) Demonstration of and RGB Playzer with an Android based application, (b) MirrorcleDraw software for demonstration, prototyping and evaluation of Mirrorcle MEMS mirrors and Scan Modules with MEMS controllers, (c) The software flow of information, converting a vector graphic image to "smart keypoints", interpolating to the correct frame rate and sample rate, and applying any transformations to correct for mounting, optical distortions and the final display surfaces.

3. MEMS MIRROR MODULE (MMM)

In modest to high power laser beam steering applications such as LiDAR and lighting, eye safety is paramount, and depends on the beam-steering component (mirror) continuously moving and correctly responding to Controller commands. Thus, the component must be monitored in position and in systems with very high laser power in temperature as well - to

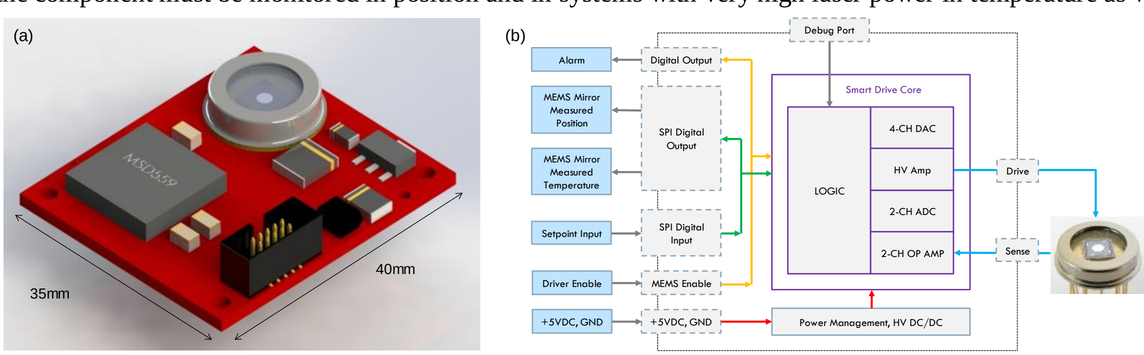

Figure 7. (a) The MEMS Mirror Module with Smart MEMS Driver design, showing the MEMS mirror in a hermetically sealed package, and the Smart MEMS driver that can drive the MEMS mirror, monitor its position and temperature, (b) A block diagram of the MMM, showing the various input / output connections available, such as the user issuing setpoints over digital SPI commands, and receiving position information and various warnings to trigger any safety systems.

warn the upstream systems if the beam stops responding or parts begin to overheat. Due to this requirement MEMS driving and sensing electronics are assembled intimately with the MEMS mirror into a compact module. This MEMS Mirror Module (Figure 7) is a versatile subsystem consisting of a gimbal-less dual-axis MEMS mirror and a Smart MEMS Driver that can very efficiently drive the MEMS mirror, monitor its temperature and position, and operate in commercial, industrial and automotive environments. In a typical application as outlined earlier, the driver is interfaced with an MCU based controller which in turn interfaces the complete sub-system to any host systems via USB, CAN bus, wirelessly via Bluetooth or Wi-Fi.

3.1 MEMS MIRROR

The MEMS Mirror Module's key component is the MEMS Mirror. While the Module could operate with practically any of the gimbal-less dual-axis MEMS mirrors, implementations so far have been focused on the automotive lighting applications and therefore the two main designs of Mirrorcle's MEMS Mirrors used in this module are: the 1.2mm diameter, Aluminum coated mirror A3I12.2-1200AL, and the 2.0mm diameter, Aluminum coated mirror A7M20.1-2000AL. Each device is packaged in a hermetically sealed TO-8 can with an AR coated cap for the specific application – e.g. 445-450nm in phosphor-based lighting, 905nm in LiDAR, or 1550nm in LiDAR and free space communication. The MEMS mirror package includes a heatsink to help remove any heat away from the MEMS mirror and lower the quality factor (Q) of the MEMS mirror. The MEMS mirror is of single-crystal Silicon construction, a robust and reliable material, making it ideal for a long operating life time. The MEMS mirrors are specified to have a Radius of Curvature (RoC) of >5m although typical values are in the 10-12m range. The large radius of curvature is achieved by coating the mirror with a very thin layer of low-stress Aluminum which also achieves excellent and very broadband reflectance. We are also investigating other coatings such as protected and blue enhanced Aluminum coatings, and Silver coatings.

There are two main categories of MEMS mirror designs: Integrated and Bonded mirror designs. In this work, only the smaller integrated designs are discussed since they have bandwidths of >1kHz, a requirement for any display related applications. In bonded mirror designs, a larger diameter coated mirror with a pedestal is bonded to the center Silicon structure, in order to have a larger reflective surface sitting in a plane above the actuator structure. These larger bonded mirrors are typically slower, with less bandwidth than the integrated mirrors, but can be up to 7.5mm in diameter, making them ideal for LiDAR and free space communication applications. The integrated MEMS mirror design is a monolithic structure with the MEMS mirror being a coated piece of Silicon structure, in plane with the combdrive actuators.

These integrated MEMS devices have a mechanical angle range of ±5° (up to ±8° in bonded mirror designs), with the wide-angle optics in the optical scan head increasing the FoV to ~40° optical angle. The 1.2mm mirror has first resonance at ~2.6kHz and 3kHz of (-3dB) bandwidth. The 2.0mm mirror has a first resonance at ~1.3kHz and 1.5kHz of bandwidth. With the heatsink in the MEMS package, the typical Quality factor of these devices is <14.

3.2 SMART MEMS DRIVER

The Smart MEMS Driver is the electronics part of the MEMS Mirror Module, providing the analog drive voltages to the MEMS mirror and monitoring the status of the mirror. Its design is based on the standard MEMS driver with added feature for monitoring of mirror position and temperature, as depicted in Figure 7b. For that purpose, the Smart MEMS Driver includes a digital block (FPGA) that processes Controller setpoint stream inputs, processes position measurements, and produces control commands to both axes drivers. Its Setpoint Input port accepts SPI commands to set the mirror position. A debug port allows for modifications and updates of control parameters. Outputs include SPI streams of mirror status, as well as separate alarm digital terminal which can alert the upstream Controller to shut down lasers if beam-steering system is failing to properly respond. The Smart MEMS Driver is powered by user provided 5V which is converted onboard to lower voltages for the logic and DAC/ADC circuits, and to high voltage for MEMS driving.

3.3 POSITION/TEMPERATURE SENSE FOR REAL TIME MONITORING

In past work we have described integration of optical position sensing with MEMS mirrors which makes the most direct measurement of mirrors tip and tilt, but cannot be utilized in all applications due to the more complex packaging and compatibility with some types of mirrors. Another method which works universally with all of our combdrive based devices but makes an indirect position measurement is Capacitive Position Sensing, or "CaPS". In this case position feedback of the mirror is taken indirectly through the position of the combdrive actuators which are linked to the mirror with well characterized flexures.

This is achieved by sending the command signals (typically <5kHz range) and an additional sense modulation signal (>50kHz) into the combdrive drive terminals. The sense modulation has a very low peak-to-peak Voltage relative to the drive signals for the MEMS mirror and a high frequency and does not perturb the mirror position. Difference of capacitance between two different sections of the combdrive results in excitation of the moving/rotating section which can be sensed through a virtual ground connection (Figure 8a, b). After amplification and demodulation this excited signal is directly related to the rotator's position. The measurement is differential and relatively insensitive to parasitic capacitances of the pads and structures.

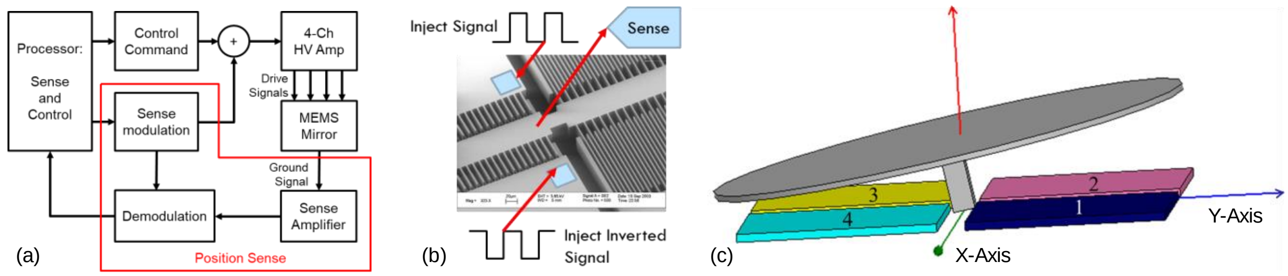

Figure 8. (a) block diagram of the Smart MEMS driver with the position sensing portion highlighted, (b) a method of capacitive position sensing by injecting a high frequency sense modulation into the combdrive drive signals, and measuring the response of the moving rotator, (c) an alternate method of capacitive sensing, by using the Si plates on the actuator, under the bonded mirror structure, to measure the proximity of the mirror to the individual plates to determine the mirror position.

An alternate method of capacitive sensing is measuring the change in capacitance between the individual Silicon plate structures that are under the MEMS mirror (Figure 8c). This method of sensing applies to bonded mirror designs since the moving mirror sits above the four sensing structures, and as the mirror tips and tilts during operation, the distance between the lowest point on the mirror and one or more of the plates (and resulting change in capacitance) is used to determine the position of the mirror. In this case, the sense modulation signal is injected into the mirror structure via the rotator ground, and the four plates are used to pick up the modulation signals. As seen in Figure 8c, plate 1 (P1), plate 2 (P2), plate 3 (P3) and plate 4 (P4) are sensed individually. To measure the X-Axis tilt, (P1 + P2) – (P3 + P4) is used, and for the Y-Axis tilt, (P2 + P3) – (P1 + P4) is used.

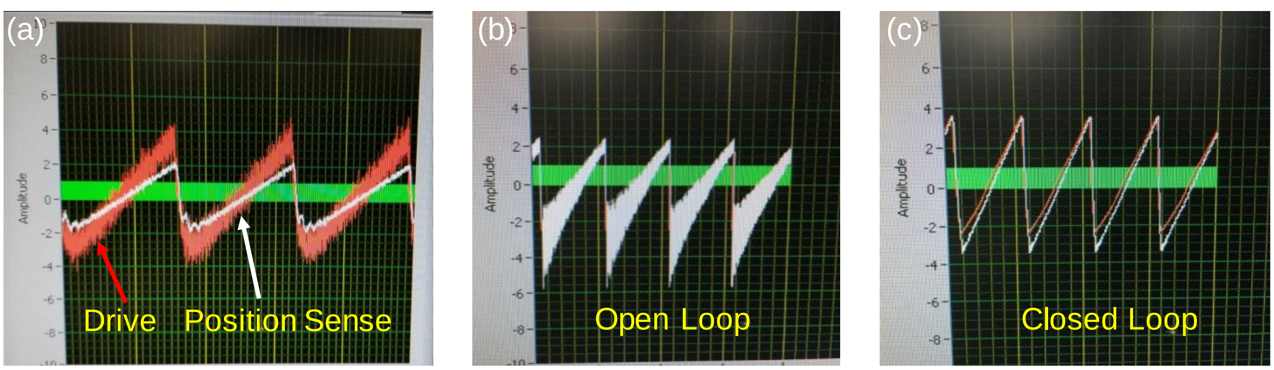

Figure 9. (a) Single-axis driving of a triangle wave in closedn loop, red is the drive signal and the white is the position sense, (b) an example of a device running a sawtooth waveform in open loop and measuring its position using CaPS and showing the device ringing, (c) the same device as (b) in closed-loop control using PID, and sensing position using CaPS.

The above capacitive sensing methodologies were initially tested by using a National Instruments based FPGA development platform and LabView for the rapid prototyping and demonstration of sensing as well as closed loop control with PID. The main advantage with the different CaPS schemes is that there is no change to the MEMS driver design. The differential sense modulation signals are added during waveform generation, and the sensing happens by measuring the response via ground signals in the case of combdrive actuator sensing, or measuring the four plates in the case of the bonded mirror plate sensing. A few different MEMS mirror designs, both integrated and bonded, were tested on the NI-FPGA platform, and some of the results are shown in Figure 9. Figure 9a shows the two different signals of a single axis sawtooth scan with a device under control. The drive signal has a lot of high frequency components as a result from a high derivative component in the PID control loop. Figure 9b shows a MEMS mirror running in open loop and the resonant frequency being excited at the return portion of the sawtooth waveform. The same waveform is shown in Figure 9c while under closed loop control using CaPS and the ringing and any excitation of the resonant frequency is removed. While these examples are of one-axis operation, position sense can be done for both axis for a two-axis device using differing excitation frequencies.

4. ROBUSTNESS AND QUALIFICATION

4.1 MEMS MIRROR COATINGS AND LASER POWER HANDLING

Mirrorcle's MEMS mirrors are typically coated with bare metal coatings of Aluminum (Al) or Gold (Au). Beyond those, experimental coatings have been done for wavelength specific High Reflectivity (HR) coatings for IR wavelengths (e.g. 1064nm and 1550nm), and protected Silver (Ag) coatings for high reflectivity with the blue wavelengths. The standard coatings of Al and Ag are very thin, allowing for the mirrors to be very flat, with RoC > 5m. The non-standard HR and Ag coatings are much thicker in coating, require thicker mirror structure, and hence add weight and stress to the MEMS mirror. The increased weight results in a significant drop in the device's bandwidth, and the stress of the coating often reduces the RoC to unacceptably low curvature. Thus, Aluminum coating is utilized in all MEMS mirrors slated for the lighting applications explained here. The ~8-10% absorbed optical power is a level that can be tolerated by the overall MEMS device and package design and the result is reliable operation in 1000s of hours at very high optical powers. The specialized, heatsinked package, uses a copper structure under the MEMS mirror to remove heat absorbed by the mirror by significantly reducing the air gap between the mirror and the package.

Multiple A3I12.2-1200AL mirrors and A7M20.1-2000AL mirrors were tested with a high power 445nm laser source to determine laser power handling and operation life times. In maximum power experiments, multiple mirrors survived peak CW power of 8W on the mirror, but some were physically damaged after >10 mins of exposure. All tested 2mm mirrors operated at 5W of CW power for 10s of hours, and all tested 1.2mm mirrors operated at 3W of CW power for 10s of hours (in both cases tests were terminated for practical purposes with no units damaged). For long term tests, multiple A7M20.1-2000AL mirrors ran for >1200 hours with 4.5W of CW power and continued to operate without any problems. The only changes noted in all the laser power testing was the reduction of RoC – curvature was increased after exposure of the mirror itself to ~200°C temperature. Through baking tests of the MEMS mirrors, we are able to determine the temperatures the mirror might be experiencing when under high laser power. The mirror surfaces were measured for flatness before and after they were elevated to 200°C or 250°C. After the laser power tests and flatness measurements, the change in flatness was higher that then that of the bake test. Using this information, it can be inferred that the mirrors are experience temperatures on the order of 250°C at the 4.5W CW power exposure. In the case of lighting applications, where the beam is scanned onto phosphor targets a few centimeters away, the change in RoC does not have much effect. Nevertheless, this is an area where improvements in processing and device preparation are being undertaken.

4.2 MECHANICAL SHOCK AND VIBRATION

Most of Mirrorcle's integrated mirror designs and a few of the bonded mirror devices have gone through anecdotal mechanical shock and vibration testing. For mechanical shock, MIL STD 883-E, Method 2002.3 was used, with 500G of shock for 1ms (Condition A) and 1500G of shock for 0.5ms impulses on all six directions (Condition B). All the integrated mirrors up to 2.0mm passed these specs, with the 2.4mm A5M24.1-2400AL mirror passing the 500G shock. Bonded mirror designs up to 3.0mm also passed the 500G spec. The integrated mirror designs with the heatsink structure had better rates of survival with no damage due to the heatsinks acting as an air damping structure under the MEMS mirror to reduce the quality factor of the device. All Mirrorcle MEMS mirrors typically pass the vibration specification, MIL STD 883-E, Method 2007.3 with 20G of vibration from 20Hz to 2000Hz. These vibrations will upset the scan of the MEMS mirror when run in open loop but will not damage the device. All devices survive this test and continue to operate without any issues.

4.3 OPERATION LIFE TIME

There have been many Mirrorcle MEMS mirror devices that have operated over the period of a decade, accumulating >10 billion cycles of operation, and continue to operate. The purely single-crystal Silicon construction of the MEMS mirror, with no rubbing parts, makes the device ideal for significant extended use given no mechanical wear over time. Various customer inspired, device specific, tests were performed by Mirrorcle, from checking continuous device operation while being over driven in voltage, operation of devices while being thermally cycled, testing devices under high laser powers, etc. On the test on continuous cycles of operation driven at 40V over the maximum rated voltage, devices completed >3 billion cycles before the first device saw any issues in operation, and most operated >4 billion cycles. These tests were done with an older assembly process, and it is believed that newer assembly processes including die attach adhesive selection will improve the life time operation, even while being driven at over voltage.

In the thermal cycling tests, batches of devices were stored in three different temperature categories: 25°C or room temperature, 65°C and 105°C. These devices remained in the temperature bath for 1 week at a time per cycle and were inspected and characterized to note any changes to the device's mechanical response. After >2500 hours of cycling, these devices continued to show no changes, and operated without any issues. This temperature cycle study was performed to test the resiliency of the MEMS mirror device as well as the assembly process of the device into its connectorized package, testing the package materials, die attach, window attach, and bonded mirror attach adhesives, etc. The devices packaged in the most recent assembly processes developed by Mirrorcle showed that there are no issues of sitting and operating at elevated temperatures up to +105°C. Mirrorcle has demonstrated operation of MEMS mirrors at a temperature range from room temperature (~25°C) up to 200°C with no noticeable changes in the device's mechanical angle or frequency response (Figure 10). The devices under test were monitored and characterized as the temperature was increased incrementally. Work done by others using Mirrorcle MEMS mirrors have demonstrated operation in temperatures as low as 4° Kelvin [17][18]. This wide range of operation, typically specified at -40°C to +105°C makes the MEMS mirror an ideal candidate for industrial, space and automotive applications that have stringent environmental requirements.

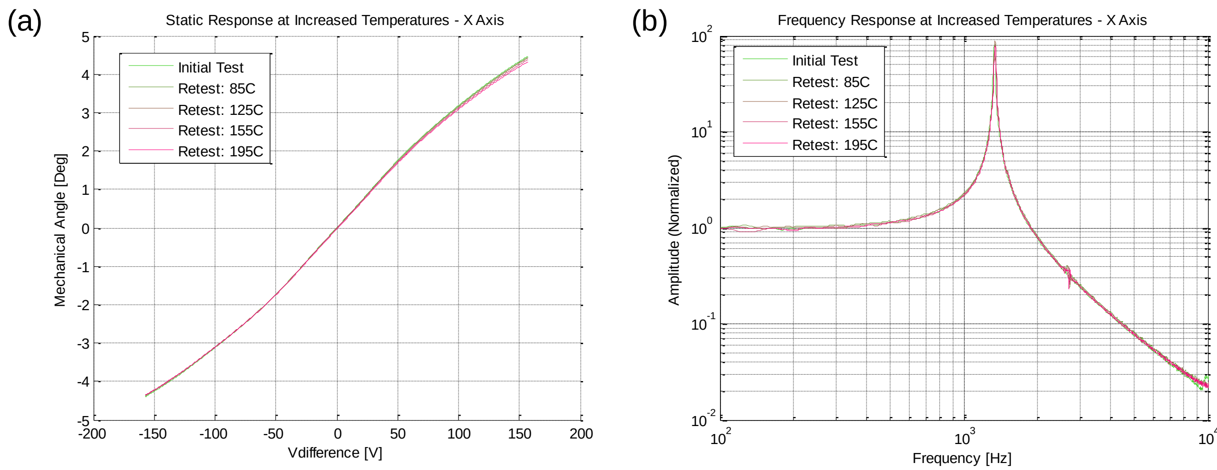

Figure 10. A7M20.1 MEMS mirror (2.0mm Al coated mirror), that is characterized from room temperature of ~25°C up to 195°C. (a) Static Response shows negligible changes in mechanical angle vs. voltage over a wide range of temperatures, (b) Small Signal Frequency Response of the device shows no changes in resonant frequency or quality factor of the device.

After demonstrating running continuously and at temperature for billions of cycles and thousands of hours, Mirrorcle has also demonstrated operation of MEMS mirror under high laser powers of 4W CW at 445nm wavelength, at room temperature for >1200 hours. Some experiments were done with the devices seeing >3W of CW power at 445nm wavelength, while operating at an elevated temperature of 65°C for a few hours at a time, in multiple cycles. In all these testing cases, all the devices passed, and continue to operate.

4.4 PATH TOWARDS AUTOMOTIVE QUALIFICATION

Mirrorcle MEMS mirrors have demonstrated robustness in mechanical shock, vibration, temperature range, and life time operation and laser power handling, proving the technology as a worthy component for automotive applications. Additional work is also being done on the manufacturing of the MEMS mirrors, looking for qualified assembly partners and working with Microchip on upgrading the driver and controller electronics to automotive qualified parts. The MEMS fabrication has advanced recently by working with two different MEMS foundries, one in Asia and one in North America. Mirrorcle already has vigorous standards when it comes to the packaging and tracking of MEMS mirrors and supporting electronics and is working its way to becoming ISO certified. These MEMS mirrors are already used in automotive LIDAR prototypes and are in the process of being qualified by customers. The goal in 2019 is to complete the process level qualifications for an already robust technology, and have a completed automotive qualified MEMS Mirror Module that can be used in automotive LIDARs, Displays and Programmable Light Systems.

4.5 IMPLEMENTATION EXAMPLE - PROGRAMMABLE LIGHT SYSTEM

The Programmable Light System or PLS is a complete high contrast white light projection system, based on Mirrorcle's VGLP Architecture (Figure 11a) and laser phosphor technology. The system consists of the blue laser Scan Module, a phosphor target, secondary projection optics, laser driver and controller electronics. The prototype PLS uses the EaZy 2.0-B1W Scan Module described above to achieve high brightness based on a 1W laser beam (Figure 5a). The phosphor target is placed approximately 27mm away from the Scan Module's output lens to have a small focused spot (~100µm x 150µm) of the scanning beam on the phosphor. The Scan Module and the target can be mounted in either a transmissive or reflective configuration [14], relative to the final projection optics. In the current version, a transmissive phosphor housed in

Aluminum for adequate cooling, is used with a 50mm f/1.2 Nikon lens for the projection optics. Earlier concepts of the PLS were demonstrated with both reflective and transmissive targets and COTS lenses from Thorlabs. The electronics consists of a Microchip PIC2MZ MCU based controller called the OCCIE with an integrated MEMS Driver and 8-bit laser driver. The PLS electronics consume a total of 6W of power, with 850mW going to the MEMS controller stack, and ~5W going to the laser and laser driver. A battery-operated version of this system is also available, running the laser at 500mW power at the Scan Module Output (Figure 11b, 11c). The entire optical system is constructed using Thorlabs parts and 3D printed housing, with overall dimensions of 185mm x 70mm x 70mm, weighing ~1kg.

Figure 11. (a) The Programmable Light System with a Nikon 50mm camera lens for projection, and the OCCIE MEMS controller with a Bluetooth module and a high current (>2A) laser driver, (b) the latest PLS module displaying "Ni Hao" Chinese characters, (c) the PLS white light projection system displaying a vector graphic, with a light-weight and compact design, and battery operated for easy mounting and demonstration of technology.

In the past both reflective and transmissive target based PLS systems have been demonstrated. As the demand for brightness and in-turn laser power increased, the phosphor target had to be reinforced to work with the higher power laser sources. The reflective phosphor greatly improves the amount of usable light for white light projection. The phosphor is attached to the reflective surface of aluminum or silver which allows any light which goes through the phosphor to be reflected back out. Having a solid backing for the phosphor also provides it with a surface to conduct heat away from the phosphor therefore reducing the likelihood of damage. Using a reflective phosphor does has its disadvantages, however. The phosphor plate would need to be parallel output projection lens to maximize the lighting. The main attractiveness of a transmissive target based PLS is the one-dimensionality of the optics stack from the laser source to the projection lens. The challenge with this method of illumination is the cooling and efficiency of the phosphor substrate. For laser light excitation of the phosphor, the laser needs to hit the phosphor so that light passes through it. Without direct heatsinking of the phosphor, the phosphor will damage from any stationary beam of high-power laser. Transmitting through a phosphor is not as efficient as a reflective phosphor because half of the converted light is radiated back towards the laser source. The transmissive phosphor can be optimized with the phosphor target structure design and coatings to improve transmission efficiency on one side and reduce the glow of the phosphor around the illuminated pixels.

The current transmissive design uses the latest Scan Module EaZy 2.0-1BW, and a custom phosphor design on a sapphire substrate and housed in an aluminum casing for heatsinking. The phosphor is designed to convert 130 Lumens / Watt, with a modified structure to reduce the glow and direct more light forward. Measurements of a single circular spot from this PLS system showed a maximum brightness of 55klx in outdoor, daylight, cloudy conditions, and a brightness of >5klx in various vector graphic content in the same outdoor, daylight cloudy conditions with a background brightness of 2klx.

5. CONCLUSIONS

The robustness of the MEMS mirror technology in mechanical shock and vibration, a wide temperature range, and a high laser power damage threshold makes it an ideal candidate for any commercial, industrial and automotive application. The MEMS Mirror Module, with the integrated MEMS mirror and smart MEMS Drive core that can monitor position and temperature, is a versatile component that can be used in a wide variety of applications. With the Vector Graphics Laser Projection Architecture, the full technical stack is available for user to develop the technology and offers the opportunity to integrate the technology at any layer along the technical stack. Applications may work with the lowest layer of integration, starting from the core component of the MEMS Mirror Module, or upgrade to a full system with a controller flashed with firmware to interface with a host system, and even utilize Windows, Android and Linux applications built on Mirrorcle's API.

The Programmable Light System is a demonstration of this Vector Graphics Laser Projection Architecture, showcasing the MEMS mirror operating with a high-powered laser in a Scan Module, being driven from the OCCIE controller and interfacing with Windows and Android applications to project vector graphic content onto a remote phosphor target, and projecting the converted white light. Some of the systems components already meet automotive qualifications in shock, temperature and life time, while other components (electronics) are being upgraded to also meet these stringent requirements. Continuous efforts are also being made on the software front, with development of new firmware and software functions that enable ease of operation and development of new applications.

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