HIGHLY ADAPTABLE MEMS-BASED DISPLAY WITH WIDE PROJECTION ANGLE

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ABSTRACT

We demonstrate a MEMS-based display system with a very wide projection angle of up to 120°. The system utilizes a gimbal-less two-axis micromirror scanner for high-speed laser beam-steering in both axes. The optical scan angle of the micromirrors is up to 16° on each axis. A custom-designed fisheye lens is utilized to magnify scan angles. The system can display a variety of vector graphics as well as multiframe animations at arbitrary refresh rates, up to the overall bandwidth limit of the MEMS device. It is also possible to operate the scanners in point-to-point scanning, resonant and/or rastering modes. The system is highly adaptable for projection on a variety of surfaces including projection on specially coated transparent surfaces (Fig. 3.) The size of the displayed area, refresh rate, display mode (vector graphic or image raster,) and many other parameters are all adjustable by the user. The small size of the MEMS devices and lens as well as the ultra-low power consumption of the MEMS devices, in the milliwatt range, makes the overall system highly portable and miniaturizable.

INTRODUCTION

Advances in mobile communications, portable computing and personal electronics have led consumers to demand large viewing area, bright, high resolution, compact and long life portable displays [1],[2]. However, to date such systems have not become available. Two of the primary challenges are size and power consumption. Vector displays have not been fully explored as a potential means of achieving portable projection displays, mainly due to a lack of available compact, low power vector scan heads. Vector displays operate by scanning the path required to trace the outline of objects being rendered while raster displays must scan the entire view field. Vector displays hence require less memory, do not suffer from aliasing or pixelation effects and are superior in applications where wireframe images are sufficient (e.g. compact heads-up and projection displays.) Vector scanning utilizes available laser power most efficiently, resulting in maximum image brightness for a given amount of input laser power. While resonant MEMS scanners have been used to demonstrate laser raster displays for video [1]-[4], vector display systems still use macroscopic galvanometer scanners [5] due to lack of MEMS scanners capable of achieving large-angle deflections over a wide bandwidth.

Our goal in this work was to demonstrate a portable, low-power, and highly adaptable or flexible display system that utilizes fast two-axis scanners to produce vector and/or raster images with a display size and field-of-view that are not limited by the MEMS device scanning angle. Wide-angle capability would allow the system to be mounted in close proximity to a display surface while still being capable of addressing a large display area. This makes the system far more flexible for uses in a variety of situations. Such a system could be mounted in a variety of places and simply re-programmed to produce distortion-corrected images on a display surface, even if that surface is highly curved. In all of the above applications, resonance-based raster scanners would not be applicable. The scanning unit must be capable of following an exact prescribed trajectory that includes lens-distortion compensation, perspective-distortion compensation, display surface curvature compensation, etc.

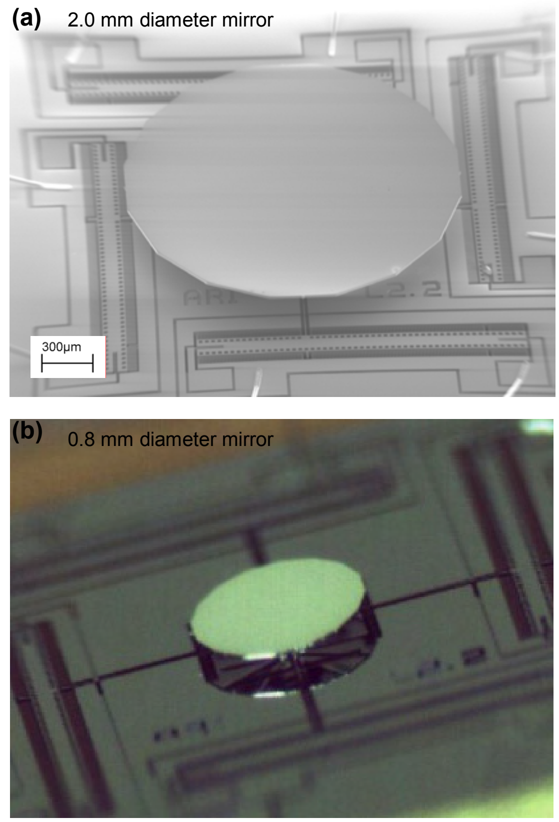

Figure 1. (a) SEM of a gimbal-less two-axis micromirror scanner with a 2mm diameter micromirror bonded on top of the actuator, (b) stereo microphotograph of another scanner with a 0.8mm diameter micromirror.

DEVICE DESIGN

We utilize gimbal-less two-axis MEMS optical scanners [6] (Fig. 1) based on monolithic, vertical combdrive actuators. The gimbal-less design results in ultra-fast two-axis beam steering with large optical deflections of >16° over the entire device bandwidth. A typical 0.8mm diameter device used in this system can operate from dc to ~4 kHz without exhibiting resonant behavior. In other words, the beam scan can directly

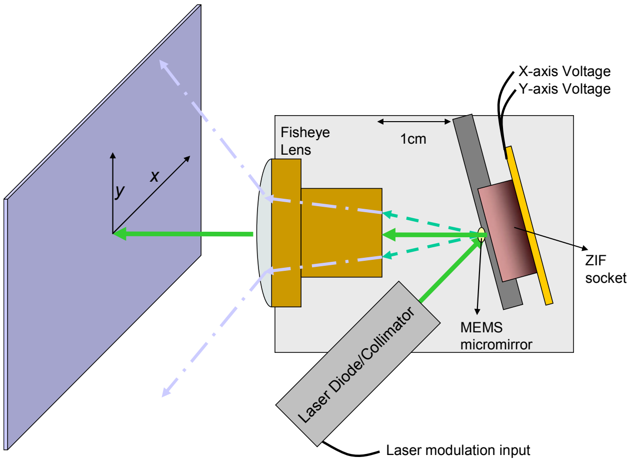

Figure 2. Schematic of display system setup: laser diode points a collimated beam onto the MEMS micromirror which deflects it into the wide-angle (fisheye) lens. The lens magnifies the deflection and projects the beam onto the display surface.

follow voltage commands on a point-to-point basis. The desired trajectories must be filtered in order to limit bandwidth of the waveform reaching the device and prevent oscillations [7]. The devices are therefore very suitable for vector graphic scanning as well as a wide variety of other applications that require point-to-point scanning.

Large-angle step settling times below 100 μs were demonstrated with customized, device-specific filtering schemes [7]. When such devices are actuated to follow a raster-pattern trajectory, there is a measurable step to step motion between pixels and brief settling/residence time on each pixel. In such cases angle-steps from pixel to pixel are very small (<0.01°,) and settling times shorter than 2 μs are observed. This is clearly visible on the displayed surface, but was also verified with a 2D position-sensitive detector (PSD) and a fast oscilloscope.

The power consumption of our MEMS scanners (< 1mW) is several orders of magnitude lower than that of similarly performing galvanometer scanners. Power consumption of the overall system is dominated by the electronics, as well as laser supply. Our overall system utilizes a dc-dc converter to ramp up the USB- or DAQ-provided +5V, in order to maintain mobility. Namely, the overall system can be fully driven from a laptop with no additional supplies.

DESIGN FOR WIDE-ANGLE PROJECTION

In order to address a large display area of 50cm x 50cm or greater with a projection distance of 20 cm to the display surface, the system requires optical angles of over 100°. We have therefore employed a custom designed fisheye lens (Fig. 2 and 3) based on 3 spherical lens elements, which magnifies the MEMS scan angles up to 7 times.

The lens design was driven by the need for a low cost of prototyping and fast turn-around. Only spherical elements were considered in the design, which was created by using ZEMAX software [8]. Due to the large required scanning angles, the resulting lens has a large F-Theta distortion at larger angles. Therefore, significant pin-cushion distortion

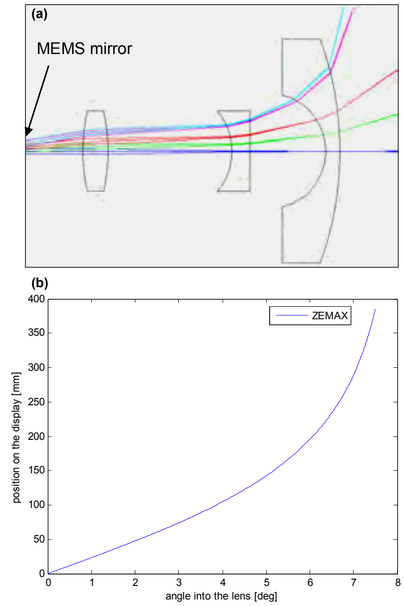

Figure 3. (a) Custom designed fisheye lens magnifies optical scan angles to over 128° (on the diagonal.) It is comprised of 3 spherical lens elements and designed to maintain a spot size of <=4mm on the display positioned 20cm away from the MEMS optical scanner. (b) Graph of optical scan angle incident to the lens vs. position on display surface away from lens-axis – obtained in ZEMAX software.

results, which requires compensation in the scan pattern of the micromirror device. In order to compensate for lens distortions, we created a look-up-table (LUT) within the optical design CAD, that provides the relationship between optical scan angle of the MEMS micromirror and the position of the laser beam on the display surface placed 200mm away from the lens. The LUT is one-dimensional due to the fact that the lens is axially symmetric. The graph is shown in Fig. 3. It can be seen clearly in the graph that for optical scan angles of the MEMS device above 4 degrees, position on the display increases drastically in a non-linear fashion.

SOFTWARE

The software 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 multiframe animations consisting of a list of keypoints for each frame. The raw path data is then interpolated to the system's sample rate, and filtered depending on the type of filter that is chosen. The simplest filtering scheme applies a digital Bessel low pass filter to prevent device's "ringing" response [7]. The final voltages for each axis are then sent using a DAQ card or a USB port to a high-voltage amplifier to get sufficient voltage to operate actuators to full <=8° mechanical deflections. In addition to correct for the nonlinear deflection of the device, it is also necessary to compensate the barreling distortion due to the lens. Fig. 4c shows the actual voltages that must be applied to obtain equally spaced points on the display surface (Fig. 4a). This mapping is implemented as a lookup table that gives the required voltages on both axes in order to reach a point on the display surface. This lookup table is experimentally determined and hence can be extended to

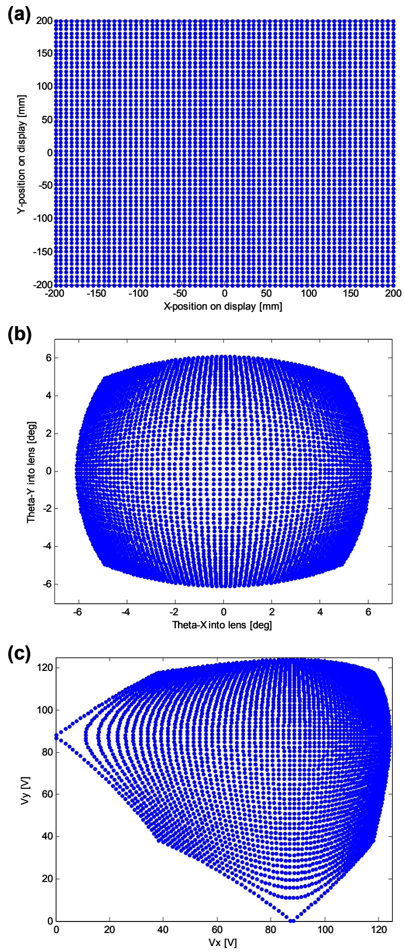

Figure 4. Lens- and device-compensation strategy example: (a) graph of equispaced points on the display surface which we would like to be able to address with the scanning system, (b) due to lens-distortion correction, required optical scan angles of the MEMS scanner at the lens are barrel distorted, and (c) due to device look up table (approx. matches square root function,) resulting voltages to the x and y axis that are required to address points in (a) are highly nonlinearly arranged.

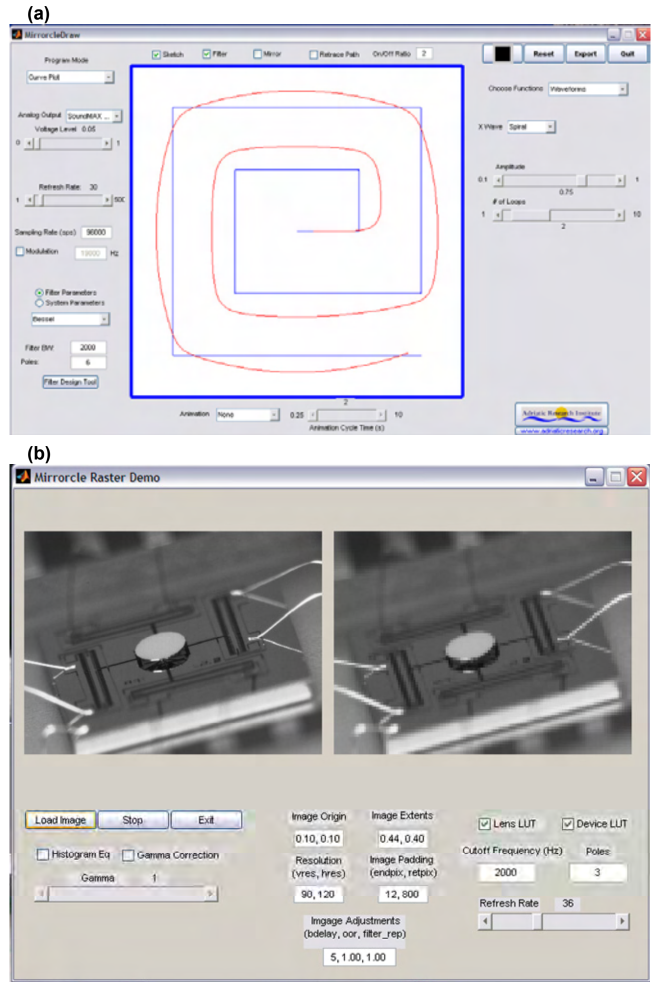

Figure 5. (a) Screen capture of the MirrorcleDraw software, demonstrating the lens correction algorithm. Blue vector graphic depicts the desired shape to be displayed, while the red trace depicts the distortion compensated and pre-filtered shape. (b) Screen capture of MirrorcleRaster software which allows a user to input an image and resample the image to the raster display size (option in the GUI,) e.g. 120x90 pixels. The software then creates a stream of x,y positions and grayscale laser commands (digital output channels) for the DAQ card.

non-planar surfaces and can also correct for perspective distortion. The main software interface is shown in Fig 5a. The software allows the user to create arbitrary sketches or animations and calculates the pre-distorted image (red) that must be output in order to display a correct image. The software also has a raster display mode where it is possible to display a grayscale bitmap image as seen in Fig. 5b. The input bitmap is first converted to grayscale and down-sampled to a small size suitable for rastering with the MEMS device. The size is a user input parameter, e.g. 120x90 pixels. The grayscale information is used to modulate the laser intensity at each pixel. The device is then made to trace out a raster pattern on a point-to-point basis, i.e. neither axis is resonated. The laser is synchronously modulated with the device in order to display the bitmap image. Synchronization with the laser blanking or modulation is trivial in this case as the device's position, i.e. tilt angle is well known since the device is not characteristics of the mirror, such as its settling time and resonant frequency. Furthermore, the image can be placed in any subsection of the full display surface by simply choosing the offset and size of the image. We have been able to demonstrate 120x90 grayscale images at refresh rates of up to 40 Hz. This method of raster display is very tunable and can be scaled to accommodate different image sizes and refresh rates since it does not depend on a single resonant mode of the device to drive the scanner. Finally, the scan pattern can be further compensated (pre-distorted) to give a proper image on a curved surface, or on a surface that is at some perspective angle from the MEMS scanning system.

Some vector frames are shown in Fig 6a,b, displayed on an opaque dark surface employing a 532nm laser. Fig. 6c,d shows examples of displaying static or animated text and Chinese characters on a special transparent surface obtained from Superimaging [6]. The surface is coated with a film that

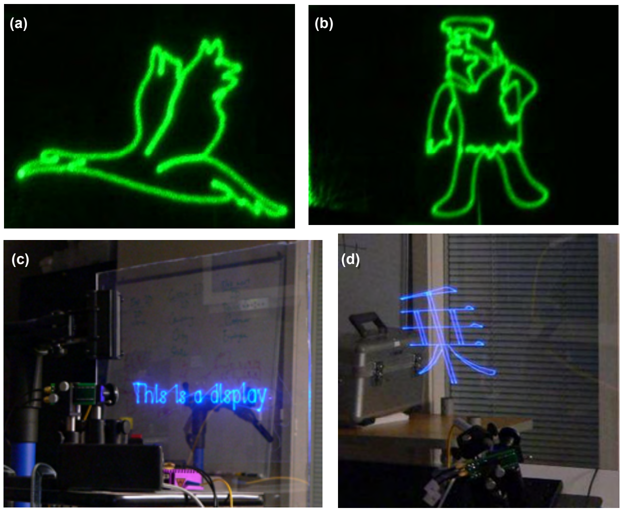

Figure 6. Display examples, (a,b) Sample frames from various multiframe vector animations. The animation time and refresh rate can be set independently and the above were rendered at 40 Hz refresh rate. (c) Displaying of static and animated text and Chinese characters on a special transparent surface obtained from Superimaging [6]. The surface is coated with a film that absorbs 370-410nm laser radiation and at a visible wavelength in all directions.

absorbs 370-410nm laser radiation and re-emits the image omni directionally at a longer, visible wavelength.

A sample rasterized bitmap image is shown in Fig. 7. The image is displayed in a section of the overall display area, which can be chosen by the user. The size of the display area and image resolution is eventually limited by the mirror speed but it is possible to choose any combination of resolution, refresh rate and size within this limit. The intensity map of the image is applied by modulating the laser synchronously with the micromirror motion. At each pixel location, a pulse-width modulated signal, with 32 brightness levels, produces the grayscale effect. This requires that the DAQ card outputs digital data at a rate of several MHz. We chose to utilize an external FPGA development board which converts the DAQ card parallel-input digital data stream to create the fast PWM signal at over 12MHz.

In certain cases, it is essential to have a tunable lag time between the laser modulation and the micromirror actuation signal in order to exactly synchronize the mirror motion and laser modulation.

CONCLUSION

The MEMS based, highly adaptable, wide angle projection display presented in this work is very promising for a wide range of applications. The display system is especially well suited for portable and mobile products, where compact size as well as minimal power consumption are critical. The compact size also makes the display very well suited for military and other heads-up-display systems. Furthermore, the wide range of user controllable parameters (display mode, refresh rate, display area) allow the system to be adapted for a variety situations and conditions. By specifically designing the lens as well as the MEMS device for a particular application a truly optimized display can be realized.

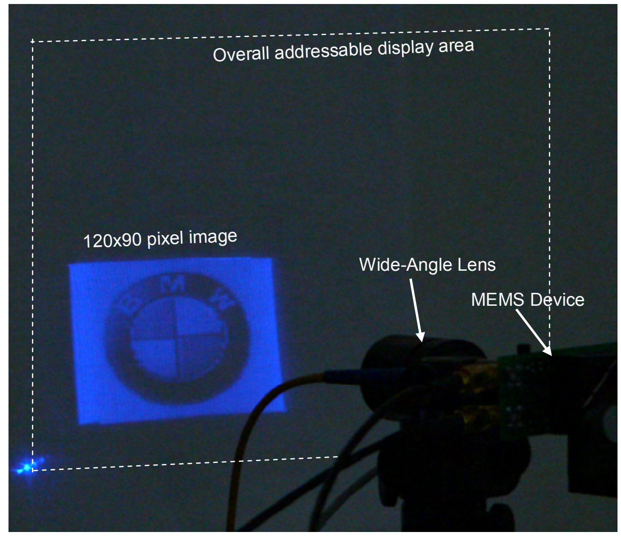

Figure 7. Display examples of a rasterized image. A 120x90 pixel image is displayed in a subsection of the overall addressable display area and the grayscale intensity is obtained by modulating laser intensity synchronously with the raster motion of the micromirror.

Advances in the performance of the MEMS devices as well as the optical system will continue to drive the realization of improved displayed systems.

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