Programmable imaging with two-axis micromirrors

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We demonstrate a means of creating a digital image by using a two-axis tilt micromirror to scan a scene. For each different orientation we extract a single gray scale value from the mirror and combine them to form a single composite image. This allows one to choose the distribution of the samples, and so in principle a variable resolution image could be created. We demonstrate this ability to control resolution and projection by constructing a voltage table that compensates for the nonlinear response of the mirrors to the applied voltage.

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Imaging systems that differ from the traditional lens-film paradigm have recently been appearing in increasing numbers. One of the earliest is coded aperture imaging, which dates back to the 1961 work of Mertz and Young.[1] This is an example of computational imaging, in which the optical system is designed to include a computational component that performs a task that is not a mere heuristic. Other examples (not attempting to be exhaustive) include Cathey and Dowksi wavefront coding introduced in 1995,[2] which allows for optical imaging with great depth of field. More recent examples include light field imaging, for which one may consult the excellent survey by Levoy.[3] Zomet and Nayar used liquid crystal masks for "lensless imaging."[4] Split aperture imaging for extended dynamic range was investigated by Aggarwal and Ahuja.[5]

Here we consider imaging with a single micromirror, as a first step to building a system that will utilize a large array. Microoptoelectromechanical systems (MOEMS) is a relatively new field that appears to have a multitude of applications. Perhaps the best-known MOEMS is Texas Instrument's digital micromirror device (DMD), which is an $N \times N$ array of static random-access memory cells, each covered by a tilting mirror.[6] Each of these mirrors is either in a binary ON or OFF state. The primary application of this device is for the projection of images.

The availability of the Texas Instruments DMD chip has resulted in a number of new approaches to imaging, such as the work by Takhar *et al.* on compressive imaging and Nayar *et al.* on programmable imaging for dynamic range and increased field of view.[7,8] Of course, medical imaging includes numerous examples of computational imaging techniques, largely based on solving inverse problems, such as CAT, ultrasound, and optical tomography, which we will not even attempt to survey.

Optical switching is another application area for MOEMS. Here, mirrors can eliminate the costly conversion from the optical domain to the electrical domain for switching. An example is Lucent's WaveStar LambdaRouter, which used an 8×8 array of two-axis 600 μm diameter micromirrors to achieve fiber array switching for 256 channels.[9] A later version of the array consisted of 16×16 mirrors. Each mirror may be individually actuated and can achieve 100,000 distinct states.[10]

In this Letter, we present our initial results on photographic imaging with using a single two-axis tilt micromirror that can operate in the kilohertz range. We demonstrate a means of calibrating the mirrors for imaging purposes and show that by choosing various voltage functions, one can program the sensor to mimic different types of lenses.

Note that while the term "imaging" is commonly associated with MOEMS, it is usually not used in the sense of photographic imaging.[11] Exceptions include work done by Nayar *et al.* with the DMD to extend dynamic range and work by Zhou *et al.* on microcameras that use a one-axis mirror to increase the field of view.[8,12] Previous work by the authors described simulations and some manual experiments.[13]

In conventional macroscopic photography, there is the notion of image mosaicing, in which one combines two or more images with some common overlap to create a single image of higher resolution than its constituents. An omnidirectional example, which is the main motivation for this work, is that done by Kropp *et al.* as part of the MIT City Scanning Project.[14] In mosaicing, a camera generally is moved to obtain images. A conceivable alternative is to point the camera at a movable mirror.[15] Here we propose the use of micromirrors for this purpose in conjunction with a video camera for the purpose of obtaining one or more pixels from each image of the recorded video and combining them to form an image. One characteristic of such a sensor is its ability to sample in a prescribed fashion. For example, if an image was recorded, then it should be possible to choose a region of the scene for closer inspection, and extract more samples from that region. This becomes particularly attractive for wide angle or panoramic imaging in which the total solid angle being imaged is large, and hence a relatively small number of pixels are allocated to a typical steradian. For example, conventional panoramic imaging systems consisting of a curved mirror and video camera have the drawback that the resolution is generally nonuniform. While it is possible to design catadioptric systems that are equiresolution, these systems still lack the ability to "zoom in" on an object of interest.[16] If a curved mirror is imaged with a micromirror though, more pixels could be taken from the regions of interest. This could be especially useful for tracking and surveillance applications.

Images were synthesized by scanning a test pattern consisting of 5 mm squares, each broken into four subsquares, two of which contained smaller checkerboard patterns, with checkers 0.5 mm in the northwest subsquare and 0.25 mm in the southeast subsquare, as depicted in Fig. 1. Using a single mirror, we extracted a single pixel (the same pixel in each case) from the micromirror. Figure 2 is a schematic of our device. Our mirror has a ±7° tilt, with voltages varying from ±120. Scanning the test pattern with uniformly spaced voltages from −105 to −65 V on one actuator and −79 to 80 V on another for a fixed single mirror, we constructed a 160×160 composite grayscale image, depicted in Fig. 3A, by extracting a single pixel from each image. The nonlinear response of the mirror to the applied voltages results in a distorted image. Nevertheless, using this composite image, it was then possible to build a nonlinear table of voltages, which could sample the image uniformly. Thus we may control how the scene is sampled. The table was built using the fact that the voltages corresponding to the corners of the checkers were known. Eighty-one sample points were chosen resulting in two 9×9 voltage tables. These were then expanded to 129×129 tables via bilinear interpolation, and this table was then used to image the same test pattern. The result appears in Fig. 3B. In both images, the 0.25 mm checkers are not visible, but the 0.5 mm checkers are, so we are at the limit of the resolution of the device. These images were created using a conventional 640×480 video camera and a

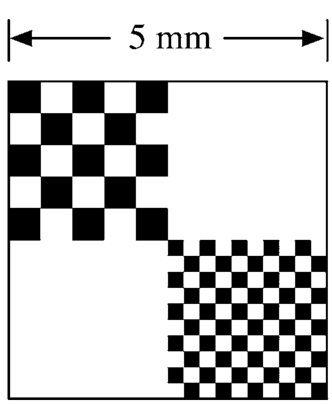

Fig. 1. Fundamental unit of our test pattern. A checkerboard pattern was chosen to allow for calibration. The two different size checkers illustrated that the resolution of the device was between 0.5 and 0.025 mm.

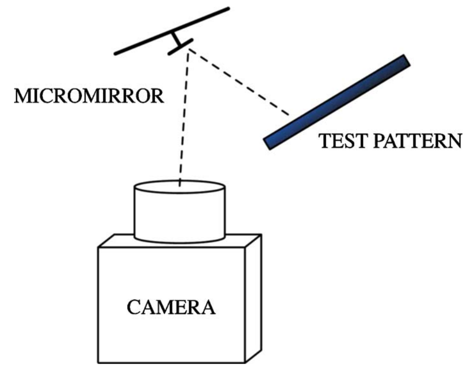

Fig. 2. (Color online) Relationship between the camera, the array, and the test pattern.

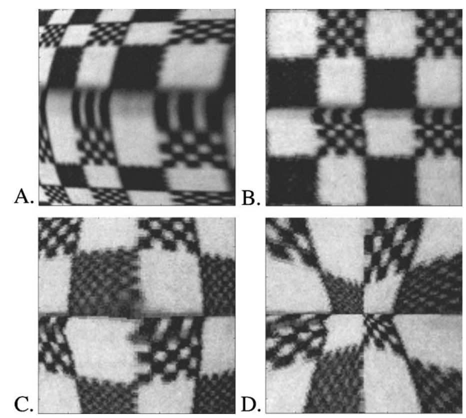

Fig. 3. Image, 160×160, created by scanning the test pattern with a single mirror and uniformly spaced voltages. B, Image, 129×129, obtained by using a nonlinear voltage table. C, Fisheye distortion can be introduced by transforming the voltage table in a radial manner. D, Pincushion distortion introduced by transforming the voltage table appropriately.

75 mm double-Gauss macrolens. Our illumination source was a 35 W halogen lamp placed 7 cm from the test pattern, which was 6 cm away from the mirror. The camera was 125 cm from the micromirror.

The advantages of imaging with micromirror arrays is the ability to choose the voltages. For example, in Fig. 3C we see a "fisheye" image formed by altering the uniform voltage table and rescanning. On the other hand, pincushion distortion can be achieved in a similar manner, as depicted by the image in Fig. 3D.

Note that for each orientation of the mirror that the "virtual viewpoint" does change but continuously. This does introduce some distortion, but all distortion is, in a sense, accounted for by choosing an appropriate voltage table.

Our work here is a proof of concept, and we have not optimized our choice of off-the-shelf lenses. Our ultimate vision is a sensor in which data were being gathered simultaneously from an entire array of micromirrors, at a high frame rate. Our main notion of a programmable sensor is that the sampling may not necessarily be uniform, but be chosen by the user. Ideally, in application, one may choose to alter the voltage table to obtain various effects, such as uniform resolution in solid angle, foveation on a particular region, or if high enough speeds could be achieved, tracking an object.

Several idealizations can be imagined to improve image resolution, quality, and increase the rate of data acquisition. First, it may be that more than a single pixel could be extracted from each mirror. Second, a two-axis tilt array with properties similar to the Texas Instruments DMD would be able to operate in the megahertz range and have small enough dead space between pixels that the array could possibly be treated as a single, continuous deformable mirror. Introducing an array of mirrors into the model raises complex questions, such as whether the mirrors could be calibrated well enough so sampling could be "interwoven" between the mirrors, perhaps allowing for superresolution. Work is being performed at several institutions to create such two-axis tilt arrays, and our hope is that the ideas introduced in this Letter will adapt to such new technology.

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References

1. L. Mertz and N. O. Young, in *Proceedings of the International Conference on Optical Instrumentation Techniques*, K. J. Habell, ed. (Chapman and Hall, 1961), p. 305.
2. E. R. Dowski, Jr., and W. T. Cathey, Appl. Opt. **34**, 1859 (1995).
3. M. Levoy, IEEE Comput. **39**, 46 (2006).
4. A. Zomet and S. Nayar, in *Proceedings of the 2006 IEEE Computer Society Conference on Computer Vision Pattern Recognition* (IEEE, 2006), p. 339.
5. M. Aggarwal and N. Ahuja, Int. J. Comput. Vis. **58**, 7 (2004).
6. L. Hornbeck, Tex. Instrum. Tech. J. **15**, 7 (1998).
7. D. Takhar, J. Laska, M. Wakin, M. Duarte, D. Baron, S. Sarvotham, K. Kelly, and R. Baraniuk, Proc. SPIE **6065**, 606509 (2006).
8. S. Nayar, V. Branzoi, and T. Boult, in *Proceedings of the 2004 IEEE Computer Society Conference on Computer Vision and Pattern Recognition* (IEEE, 2004), p. 436.
9. D. Bishop, C. R. Giles, and S. Das, Sci. Am. **248**, 88 (2001).
10. J. Kim, C. J. Nuzman, B. Kumar, D. F. Lieuwen, J. S. Kraus, A. Weiss, C. P. Lichtenwalner, A. R. Papazian, R. E. Frahm, N. R. Basavanhally, D. A. Ramsey, V. A. Aksyuk, F. Pardo, M. E. Simon, V. Lifton, H. B. Chan, M. Haueis, A. Gasparyan, H. R. Shea, S. Arney, C. A. Bolle, P. R. Kolodner, R. Ryf, D. T. Neilson, and J. V. Gates, IEEE Photonics Technol. Lett. **11**, 1537 (2003).
11. B. Gogoi, H. Urey, and D. Dickensheets, eds., Proc. SPIE **6114** (2006).
12. L. Zhou, M. Last, V. Milanovic, J. Kahn, and K. Pister, in *Proceedings of the Eurosensors 2003*, Guimaraes, Portugal (2003).
13. V. Nasis, R. Hicks, and T. Kurzweg, Proc. SPIE **6114**, 61140N (2006).
14. A. Kropp, N. Master, and S. Teller, in *Proceedings of the IEEE Workshop on Omnidirectional Vision* (IEEE, 2000), p. 47.
15. T. Nakao and A. Kashitani, in *Proceedings of the IEEE International Conference on Image Processing* (IEEE, 2001), p. 1045.
16. R. Hicks and R. Perline, Appl. Opt. **44**, 6108 (2005).