Towards a 1mm^3 Camera -- The Field Stitching Micromirror

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Summary: *The concept of a movable mirror that can be used to extend the field of view and effective resolution of any camera is introduced. For millimeter-scale and smaller cameras, this is especially important since the number of pixels in the imaging array is severely limited. MEMS micromirrors are well suited for this application. Proof of concept using a 1-axis SOI micromirror is presented. Scaling laws for small cameras are discussed.*

Keywords: *post objective scan, field stitching, micromirror, MEMS, SOI, gimbal, electrostatic, camera*
Category: *4 (Non-magnetic Physical Devices)*

1 Introduction

1.1 Field Stitching Camera

CMOS imaging arrays have shrunk the size of commercially available cameras to just a few cubic centimeters. While small by most metrics, this is still much too large for envisioned microrobotic applications. Eventually, these cameras will shrink to just a single chip with an imaging lens with a minimal amount of packaging holding the system together [2]. The volume of this type of device is limited by the number of pixels, the pixel size, and the diameter of the imaging lens. Increasing resolution (# pixels), field of view (pixel size), or light sensitivity (lens diameter) will be attainable only by increasing the total volume of the system. We propose building a hybrid camera consisting of a very small imaging array and lens coupled with a movable mirror used to choose the field of view of the camera, similar to [1]. The mirror therefore multiplies the effective number of pixels in the array. The cost of this approach is a reduction in the effective sensitivity of the camera since each pixel is time multiplexed across multiple fields of view. However, this tradeoff might be required for extremely small cameras. For instance, using 10μm pixels, a 0.5mm x 0.5mm imaging array would have only 50x50 pixel resolution. In order to achieve high resolution for a camera this small, either the pixel pitch must be reduced substantially or field stitching must be used. This paper describes the optical setup and system design considerations for a field stitching camera. Proof of concept using a custom MEMS micromirror is demonstrated.

1.2 MEMS Micromirror

MEMS micromirrors have several features that make them uniquely suited for this application. Due to their small mass, they can be moved from field to field in milliseconds, enabling camera full-scene frame rates limited only by the sensitivity of the photodiode pixels. The extreme flatness (<30nm max deviation from mean) of the SOI (Silicon-on-Insulator) micromirrors developed in our lab (fig. 1) add negligible amounts of aberration to the optical system. Electrostatic actuation requires only microwatts; this is critical for power-limited applications such as sensor networks and microrobotics. Ongoing research in our lab focuses on reducing the mirror step response time and power consumption while increasing accuracy and range of motion.

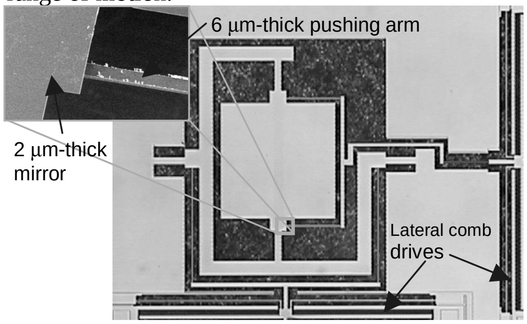

Fig. 1: A 2 axis scanner realized by a SOI/SOI bonding process. The central mirror is suspended by a double-axis gimbal structure that rotates about the two in-plane axes using orthogonally oriented torsion springs. A single-axis version was used for proof of concept experiment.

2 Proof of Concept

Fig. 2 shows the concept of the field stitching camera. A small camera consisting of an objective lens and an imaging array has a limited field of view and resolution. A mirror, placed *closer* to the camera than the focus is used to steer the camera's field of view. The original field of view of the camera becomes one of several sub-fields that selected with the mirror and stitched together to form a complete image.

This concept was tested using a long working distance inspection microscope coupled to a digital still camera. A mask constructed using a laser printed transparency was used to block rays bouncing off of the shiny substrate surrounding the mirror. Imperfect blocking of these alternate paths creates superimposed “ghost images” that do not move when the field stitching mirror rotates. The image in fig. 3 was acquired using this system and the final image consisting of three mirror positions was stitched together in photoshop.

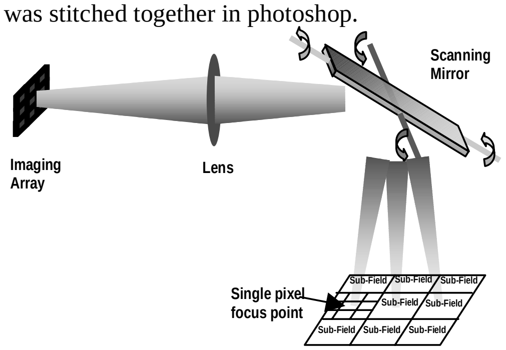

Fig. 2: Diagram of field stitching camera. A static camera field of view (“sub-field”) is scanned in a 3x3 grid, increasing the field of view and effective resolution of the camera by a factor of 9.

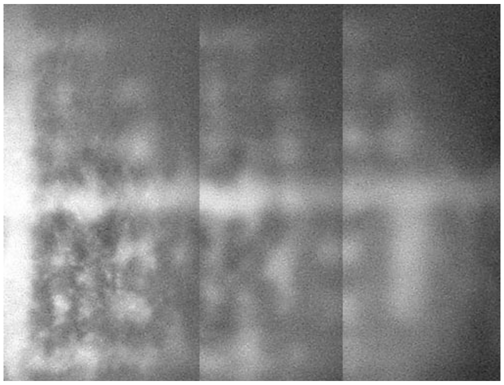

Fig. 3: Image formed using a 3x1 field-stitching camera. Field of view extended using MEMS field stitching mirror. Top row of text is reflection off substrate (note only “BER” visible), bottom row is reflection through mirror (“BERKELE” visible). Blurring is caused by field curvature and camera autofocus.

Field curvature is an issue with this type of camera. Because the mirror rotates the field of view instead of translating it, the field of view is spherical instead of flat. A variable focus lens can be used to flatten the field if necessary.

3 Scaling Considerations

The ideal way to shrink a camera is to scale every dimension down by the same factor until the either the diffraction-limited resolution is the same as the pixel resolution, or technology-imposed limits on pixel size preclude shrinking each pixel any further. Once this scaling limit has been reached, a ray-optics analysis shows any further reduction in the imager-lens distance results in a reduction angular resolution of each pixel. However, from a diffraction perspective, the increase in NA as the imager gets closer to the lens increases the angular resolution of the system. Setting the size of the pixels equal to the diffraction limited spot formed by the lens, the optimal location for the back focal length of the camera is found to be $f = \dfrac{0.61\lambda}{2NA\tan\left(\dfrac{\theta_{fov}}{2}\right)}$, where λ is the wavelength of light, θ_{fov} is the angular field of view of a pixel, and NA is the numerical aperture of the lens. In this way, an upper bound on resolution sets the lower bound on the length of the camera.

While diffraction and pixel size limit the resolution and length of the camera, the lens aperture limits the light collecting ability of the camera. Operating the imager at a constant signal-to-noise ratio (SNR), linear downward scaling of the aperture diameter results in a quadratic increase in exposure time. The field stitching mirror compounds this low-light problem, since each pixel is time-shared amongst the subfields of the camera. For an NxN field stitching camera, there is an N^2 increase in exposure time when SNR is kept constant.

4 Conclusion and Future Work

As we scale cameras to smaller sizes, diffraction and pixel pitch issues limit the resolution available in a standard camera. By adding a field stitching micromirror, this resolution can be recovered at the expense of increased exposure time. Our current work focuses on building an integrated system consisting of an 8x8 photodiode array and microlens.

5 References

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