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Development of image mappers for hyperspectral biomedical imaging applications

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Abstract

A new design and fabrication method is presented for creating large-format (>100 mirror facets) image mappers for a snapshot hyperspectral biomedical imaging system called an image mapping spectrometer (IMS). To verify this approach a 250 facet image mapper with 25 multiple-tilt angles is designed for a compact IMS that groups the 25 subpupils in a 5×5 matrix residing within a single collecting objective's pupil. The image mapper is fabricated by precision diamond raster fly cutting using surface-shaped tools. The individual mirror facets have minimal edge eating, tilt errors of <1 mrad, and an average roughness of 5.4 nm.

1. Introduction

Snapshot imaging spectrometers based on integral field spectroscopy have recently been developed for the astronomical community, providing a powerful new tool capable of collecting a 3D (x, y, λ) data cube in a single integration event [1–8]. This simultaneous data collection is crucial for obtaining high-fidelity image and spectroscopy information of low-light-level objects such as distant galaxies, planets, and stars. This technique relies on the use of arrays of high-precision miniature optical elements located near a conjugate image plane. These components are very difficult to fabricate and often become the limiting factor in the performance of the system. Our group recently developed a new snapshot hyperspectral imaging technique called an image mapping spectrometer (IMS) for fluorescence microscopy [9]. The IMS relies on the use of an array of high-precision, miniature optical elements called an image mapper, which is placed near a conjugate image plane. The requirements for the image mapper differ from those used in astronomy in that the individual elements are much smaller, more densely packed together, and have more complex individual geometries (i.e., compound angles). It is this unique combination of parameters that allows the IMS to provide higher spatial sampling ($>100 \times 100$ points), diffraction-limited resolution, and a compact size, making it ideal for use in biomedical applications.

Astronomical groups have developed many fabrication techniques for creating their arrays (called image slicers), which were considered during the development of the image mapper. In general these techniques are all based on two main technological approaches, the first, grinding and polishing, and the second, diamond machining. Grinding and polishing approaches have been reported to achieve state-of-the-art optical surface qualities with form accuracies of $\lambda=100$ rms and $\lambda=20$ proportion-of-total variance and roughness of 0.3–0.4 nm [10]. However, alignment of the individual elements is a tedious, manual process often

susceptible to individual geometrical errors as well as errors from neighboring elements that accumulate as the total image slicer is assembled [11]. For a large number of elements these errors can become quite significant. Recently, Vivès *et al.* reported a new method for making image slicers that is more cost effective and holds tighter geometrical tolerances with tilt errors <0.07 mrad proportion-of-total variance and edge quality of $1\text{--}5\text{ }\mu\text{m}$ [10]. One disadvantage of this technique, however, is that the overall number of elements is low ($\leq 60 \times 60$), limiting its usefulness for applications that require large-format imaging like those found in microscopy.

Diamond machining techniques, on the other hand, are capable of achieving higher numbers of elements (100s–1000s) with relative ease by cutting directly into a single monolithic substrate. No individual element alignment or assembly is required. By use of this fabrication approach high geometrical accuracies, tip-tilt errors of 0.2 mrad, and focus position errors of around $1\text{ }\mu\text{m}$ [12] can be achieved. The main drawback with diamond machining is a lower optical surface quality for the individual elements, with roughness around $10\text{--}20\text{ nm rms}$ [12–14]. This can decrease the optical throughput and image contrast, especially for systems with multiple diamond machined components like those used in astronomy. For the IMS system the image mapper is the only diamond machined component; therefore the decrease in optical throughput due to surface roughness should be minimal. It should be pointed out that post-diamond-machining techniques such as ductile grinding [15], ion beam polishing [15], and smoothing films [16] are being developed to minimize the roughness, although results similar to polishing have yet to be reported. Important work is also being carried out to develop cost-effective replication techniques [13] by using diamond machined substrates as the master mold. This is an important development for the image mapper, as high volumes and lower costs will be critical for broad acceptance of the IMS in the biomedical field. For all of these reasons diamond machining was chosen as an appropriate fabrication technology for the image mapper.

This paper presents our work toward designing and fabricating these new image mappers based on diamond machining technology. The image mapper design incorporates a large-format (285 element) array of high precision multiple-tilt (x and y) miniature mirrors that produces a final image matching the size of a single CCD sensor. A detailed design analysis based on both geometric and diffraction-based methods is presented in Section 2. To fabricate this complex geometry, a new fabrication method is also presented that uses surface-shaped tools to cut the individual mirror cross sections. The tools work in a raster fly cutting configuration on a four axis (X ; Y ; Z ; C) diamond lathe, which precisely controls the orientation and number of mirror facets in the image mapper. This approach represents a significant development, as it opens up the possibility to create densely packed, multiple-tilt mirror arrays without significant compromise to surface quality or increased fabrication time. To test this approach a 285-element, 25-tilt image mapper is designed, fabricated, and tested. The fabrication setup and process for this image mapper are discussed in more detail in Section 3, followed by the individual mirror facet characterization in Section 4. Last, the optical performance of the image mapper is evaluated in Section 5.

2. Optical Design

A. Image Mapping Spectrometer

The basic configuration of the IMS system for fluorescence microscopy is shown in Fig. 1 (a). The IMS consists of six components. A telecentric relay lens system (1) transfers the image from the side port of a conventional microscope onto the image mapper (2). The image mapper is composed of miniature mirror facets that reflect thin 1D mapped image lines in different directions depending on the facet's tilt angle. The image mappings are reflected toward a large-field-of-view (FOV), high-NA telecentric collecting lens (3) that collects and transfers each image mapping to its pupil plane. Similarly tilted image mappings are grouped in different regions of the pupil, forming an array of subpupils. A dispersing prism (4) is used to spread

the spectrum from each subpupil in a perpendicular direction to the linear mapping. An array of lenses (5) is placed behind the prism, forming an array of subimages on a CCD detector (5). Each subimage is composed of a dispersed mapping of the original image. Figure 1(b) shows an illustration of what the final image looks like on the detector prior to dispersing. For clarity only 4 out of the 25 grouped subimages is shown. Each subimage contains only a selected mapping of the original image with optically void space between each column of linear mappings. Insertion of the dispersing prism spreads the spectrum from each linear mapping into this void region, where it is recorded directly by the detector. Simple image remapping techniques can then be used to reconstruct the original object in real time if needed. This is advantageous for applications that require a fast temporal response. In principle, this technique also preserves the throughput (étendue) of the system, making it an ideal approach for many low-light applications such as fluorescence microscopy. A more detailed description of the operating principle of the IMS system is presented by Gao [9].

B. Image Mapper Geometric Design

One of the most important aspects of the IMS design is its compact size, being able to collect its full 3D ($x; y; \lambda$) data cube on a single CCD detector. To accomplish this and still maintain high spatial resolution requires an image mapper with a large number of tiny mirror facets tilted in multiple x and y directions. This multiple-tilt configuration more efficiently uses the pupil of a single collecting lens, creating a closely packed array of subpupils (see Fig. 2). This is necessary for forming a final image that matches the size and format of available CCD detectors. This compact design approach does not come without its share of design challenges. There are two main geometric design constraints that limit the information capacity (i.e., volume) of the 3D ($x; y; \lambda$) data cube. The first is the size of the collecting lens's FOV relative to the length and width of the individual mirror facets. This parameter determines the number of points or spatial samples in the image. For example, if FOV = 10 mm and the mirror facet dimensions are 0.1 mm $\times$ 10 mm (width and length), then a total of 100 mirror facets reside within the FOV, providing a spatially sampled image of 100 $\times$ 100. The mirror facets are designed to sample the incident image's point spread function in both directions at the Rayleigh criteria to maintain diffraction-limited resolution. Here we assume that the relay optics either match or overfill the FOV of the collecting objective and that the point spread function on the image mapper and CCD camera is also sampled at the Rayleigh criteria. The second main design constraint is the number of tilt angles for the mirror facets. Each tilt angle has a proportional relationship to the spectral sampling of the system. As the total number of tilt angles in both x and y increases, the void region between the image linear mappings [see Fig. 1(b)] increases, creating more space for sampling the spectrum in each linear mapping. The limiting factor for the spectral sampling becomes the NA of the collecting objective, which constrains the number and magnitude of the tilts. For an $L_x \times L_y$ (x and y axis) tilt geometry,

the collecting objective must have a minimum $NA_{\text{collect}} = NA_{\text{mapper}} \sqrt{L_x^2 + L_y^2}$, where NA_{mapper} is the input NA on the image mapper and $L_{x,y}$ is the number of tilt angles (x or y) as shown in Fig. 2(a).

As one can see, the collecting objective and image mapper must be designed together to maximize the 3D $x; y; \lambda$ data cube. For example, the system presented by Gao *et al.* [9] used a commercially available tube lens as the collecting objective, having a FOV of ~ 1 in (25 mm) and NA of 0.030. This lens limited the spatial sampling of the system to around 100, as the minimum mirror width fabricated was 160 μm . The number of tilt angles was also limited to a $5 \times 5 = 25$ tilt geometry owing to the small NA. Larger-format image mappers (>100) require a collecting objective with a larger FOV and NA. Recently, an objective lens designed primarily for common-path stereomicroscopy systems has been identified as a possible alternative lens. This new collecting objective provides a FOV of 30 mm with a NA = 0.150 as measured, permitting more spatial and spectral sampling.

C. Image Mapping Diffraction Design

Diffraction effects due to the small and densely packed mirror facets in the image mapper become more prominent for higher sampling IMS systems. This leads to light leaking into neighboring subpupils (also called cross talk) in the grouped pupil plane, which will degrade the final image contrast. Therefore, a theoretical model based on scalar diffraction theory was developed for analyzing the effects of diffraction [17] between the entrance pupil plane and the plane of the grouped exit pupils. The results from this model have been used to optimize the image mapper design. The basic configuration between the pupil planes of the IMS (see Fig. 1) can be treated as a standard 4-*f* imaging system as illustrated in Fig. 3.

In this model L1 is the second relay lens and L2 is the collecting lens. The following assumptions and simplifications were made: (1) unity magnification (i.e., focal lengths, *f*, are the same) as this affects only the overall scaling of the system, not the amount of cross talk; (2) the paraxial approximation, (3) a quasi-monochromatic source, and (4) a large fluorescent object such that the entrance pupil is incoherently illuminated. This simplification is valid for objects that fill close to the entire field of view of the microscope, as is the case for many high-magnification applications. For more sparse objects, the model should be adapted to consider partial coherence effects. In addition, a coherent transfer function and point spread function are presented for simplification of the mathematics and later converted to the incoherent case. These functions are used for relating the different pupil planes and should not be confused with the functions for the object or image planes.

The entrance pupil for this analysis is a circular aperture uniformly and incoherently illuminated by a fluorescent sample (not shown). Under this illumination, the grouped exit

pupil's mean irradiance, $I_{im}^{-(s)}(x, y)$, is then a 2D convolution of the entrance pupil's mean irradiance, $I_{obj}(x, y)$ with the pupil's incoherent point spread function, $P_{incoh}(x, y)$:

$$I_{im}^{-(s)}(x, y) = I_{obj}(x, y) * P_{incoh}(x, y). \quad (1)$$

The pupil's coherent transfer function $P_{coh}(\xi, \eta)$ is the complex amplitude transmittance $t(\xi, \eta)$ of the image mapper, multiplied by a linear phase of factor, which will be ignored as it has no consequence for the final result:

$$P_{coh}(\xi, \eta) = \exp(4ikf) t(\lambda f \xi, \lambda f \eta), \quad (2)$$

where ξ, η are the spatial frequencies, k is the wave number equal to $2\pi/\lambda$, and f is the focal length of the lens. The transmittance function of the image mapper is

$$t(x, y) = \underbrace{\text{rect}\left(\frac{x}{w}, \frac{y}{l}\right)}_{(I)} \underbrace{\sum_{j=1}^M \sum_{k=1}^N \exp[i2\pi(\alpha_j x + \beta_k y)]}_{(II)} \times \underbrace{\sum_{m=-\infty}^{\infty} \text{rect}\left(\frac{x - mc - (j+k-2)b}{b}\right)}_{(III)}. \quad (3)$$

Part (I) of this equation defines the overall size of the image mapper, where w and l are the width and length, respectively. Part (II) defines the linear phase introduced by each individual mirror facet in the image mapper. This phase is 2D, where α_j and β_k are equal to twice the tilt angle ($\alpha_j = 2\theta_x, \beta_k = 2\theta_y$) of the mirror facet because of reflection. Part (III) defines the width, b , of the individual mirror facets, and c is the period equal to $c = N \times M \times b$. The $(j + k - 2)$ term corresponds to a lateral shift in the origin of the repeating mirror facets with similar tilts. For this model the image mapper is treated as a thin phase object even though it is placed at a

20° angle with respect to the incoming light, which creates an axial (z -) position range of ± 3.6 mm. This is due to the large depth of focus of the incident image, which is ± 4.3 mm based on the Rayleigh depth of focus criteria [18]. For designs in which the image mapper exceeds the depth of focus, modifications to the theory will be required.

The pupil's coherent point spread function, $p_{coh}(x, y)$, of the system is the Fourier transform of the coherent transfer function, which for our system becomes

$$p_{coh}(x, y) \propto \underset{(I)}{\text{sinc}\left(\frac{wx}{\lambda f}, \frac{ly}{\lambda f}\right)} * \sum_{j=1}^M \sum_{k=1}^N \sum_{m=-\infty}^{\infty} \times \underset{(II)}{\exp(i\phi_{j,k})} \underset{(III)}{\text{sinc}\left(\frac{bx}{\lambda f}\right)} \underset{(IV)}{\delta\left(x - \frac{m\lambda f}{c}\right)} * \underset{(V)}{\delta(x - \alpha_j \lambda f, y - \beta_k \lambda f)}. \quad (4)$$

Part (I) of Eq. (4) is a 2D sinc function that is convolved with the rest of the equation. This sinc function is the resulting diffraction pattern created by the image mapper's total length and width ($l \times w$). Because of the relatively large size of l and w the associated diffraction pattern is small, with the first zero position of the sinc function occurring very close to its center at $\lambda f/w$ or $\lambda f/l$, which is of the order of a few micrometers for our typical system parameters ($l, w \frac{1}{4} 20$ mm, $\lambda = 0.5 \times 10^{-3}$ mm, $f 90$ mm). Part (II) of the equation is a linear phase factor introduced by the shift in the x direction for each set of repeating similarly tilted mirror facets (i.e., the same $j + k$ values), $\phi_{j,k} = 2\pi c(j + k - 2)$, and should have little effect on the system. Part (III) is the result of diffraction from the individual facet widths, b , and has a significant effect, with the first zero occurring at $\lambda f/b$, which is of the order of a millimeter for our typical system parameters. This sinc function acts as an envelope for a sampling comb function described in part (IV), which has a period of $\lambda f/c$. As c increases (i.e., more tilt angles (M, N) or wider facets, b) the sample spacing decreases, and there are more diffraction orders within the envelope. The last part of this equation, part (V), is a convolving 2D δ function that shifts these diffraction orders in both the x and y directions based on the tilt of the facet (α_j, β_k). The incoherent point spread function $p_{incoh}(x, y)$ is the squared modulus of the coherent pointspread function, $p_{coh}(x, y)$, which removes all the phase dependence:

$$p_{incoh}(x, y) = A_c |p_{coh}(x, y)|^2. \quad (5)$$

Based on this model it is apparent that the x axis is most susceptible to cross talk between the subpupils due to diffraction effects caused primarily by the sinc function in Eq. (4), part (IV). This sinc is the result of diffraction from the individual mirror facet's width and spreads light into the x - direction of the pupil array. As the width becomes smaller, more light spreads out, this can overlap into adjacent pupils, creating cross talk between systems. This effect is unaccounted for in the simple geometric consideration.

D. Cross-Talk Analysis

To quantify the amount of cross talk between neighboring pupils in the x direction we simulated a worst-case irradiance profile of a single subpupil [see Fig. 4(a)] in which the sampling comb function [part III of Eq. (4)] samples every point of the sinc envelope. A circular mask of diameter equal to the original pupil diameter is translated across this diffraction pattern in the x axis [see Fig. 4(b)], simulating different positions for a neighboring subpupil. Cross talk is defined as the irradiance falling inside this mask. Simulation results show that the x position at which the neighboring subpupil has only 1% of the adjacent pupil's irradiance is

$$x_{1\%} = \frac{2.7\lambda f}{b}. \quad (6)$$

The mirror facet tilt angle corresponding to this x position is then

$$\alpha_{1\%} = \frac{x_{1\%} 1.35\lambda}{f b}. \quad (7)$$

This relationship is valid only for Rayleigh sampling where $b = 0.61\lambda/\text{NA}_{\text{IMAGE MAPPER}}$. For the conditions above Rayleigh sampling, the cross talk will decrease from this value. Conversely, below Rayleigh sampling the cross talk will increase. Owing to this diffraction effect the minimum NA for the collecting objective must increase $\sim 2\times$ above the geometric limit. Assuming uniform spacing between the subpupils, the resulting minimum NA for the collecting objective becomes

$$\text{NA}_{\text{min collect}} = 2.21 \text{NA}_{\text{mapper}} \sqrt{L_x^2 + L_y^2}. \quad (8)$$

E. Image Mapper Complete Optical Design

Taking into account both geometric and diffraction-based models, we have developed an image mapper for use in a large-format IMS system capable of acquiring a 3D (x, y, λ) $250 \times 250 \times 60$ data cube while utilizing a new collecting objective identified in Subsection 2.B. The image mapper's critical optical design features are listed in Table 1.

The collecting objective for the system meets the minimum NA requirement established by the diffraction model ($\text{NA}_{\text{min collect}} = 0.063$ and $\alpha_{1\%} = 0.009$, $\lambda = 500$ nm). The number of mirror facets, $20 \text{ mm}/0.075 \text{ mm} = 267$ facets, meets the spatial sampling requirement (250 elements) while remaining within the FOV constraint of the collecting objective. Finally, the input NA from the relay optics creates a spot size diameter of $153 \mu\text{m}$, which can be sampled by the image mapper's $75 \mu\text{m}$ wide facets at the required Rayleigh sampling criteria. Note that the spot size is defined as the diameter between the first zeros of the resulting Airy disk diffraction pattern for a single point in the object. In addition to the optical design of the image mapper, manufacturing considerations also play an equally important role in the development process and are discussed in the next section.

3. Optical Fabrication

A. Raster Fly Cutting

The three main configurations for high-precision diamond machining are turning, milling, and raster fly cutting. Diamond raster fly cutting is the most appropriate approach for creating thin, straight, high-aspect-ratio features such as mirror facets for the image mapper. In diamond raster fly cutting the tool rotates about the spindle and scoops material out of the workpiece (i.e., image mapper); see Fig. 5(a). For this example, the workpiece moves up and down on the Y axis to create a thin mirror facet. To create adjacent facets the workpiece then steps over on the Z axis as shown in Fig. 5(b). This is repeated down the length of the image mapper until the entire surface is cut. A close up of the tool cutting the workpiece [Fig. 5(b)] illustrates how adjacent mirror facets with different tilt angles can be cut by the diamond tool. Here the different facet angles correspond to height variations in the workpiece at a specific X - Z plane.

Other groups [12,15] have used raster fly cutting to produce much larger mirror facets; however, compact, higher-sampling (>100 elements) image mappers require much smaller mirror facets. By scaling down the width of the facets, tools that are preshaped for the cross-section profile of the mirror facets can be used. This has several advantages, including a significant reduction in fabrication time, program simplicity, a more densely packed mirror

array, and high relative geometric accuracy independent of machine precision for axes perpendicular to the cutting direction. The disadvantage of this approach is that there is little ability to correct for errors in the cross section of the mirror facet due to the tool shape, chips, and/or other defects. This makes the quality of the diamond tools a critical component in the fabrication process.

B. Tool Design

There are several design parameters that must be considered for the surface-shaped diamond tools, such as the included angle θ , primary side clearance angle α , primary tip clearance angle ϕ , top rake angle β , tool width, maximum depth of cut, edge quality, and material. These geometric parameters are illustrated in Fig. 6.

The flat bottom tool tip width and the maximum depth of cut are the key design parameters of the tool, as they are determined by the optical design of the system. The tool tip width becomes the width of the mirror facet, while the maximum depth of cut determines the largest achievable y-axis tilt. Proper selection of the other tool parameters is critical for optimum cutting performance, durability, tool manufacturability, and overall cost. It is best to consult with the tool manufacturer to determine the various design trade-offs for each parameter as it relates to the overall design. We have developed three different tool designs for our image mappers. These tools were manufactured by Chardon Tool, Chardon, Ohio, USA. Table 2 lists the different design specifications for each tool.

Tool 1 was the first tool used to fabricate the 100 element image mapper used in the snapshot imaging spectrometer for the fluorescence microscope [9]. This tool has a 160 μm wide flat bottom tip and was used to create a square-shaped image mapper with a side length of 16 mm. In the pursuit of a large-format IMS system that still resides within the same FOV, a 75 μm flat bottom tool (tool 2) was developed. This tool increases the number of mirror facets to ~ 285 . The last tool design (tool 3) is also 75 μm but has a reduced included angle to minimize the effects of edge eating. The edge eating effect is due to height differences from adjacent y-tilt facets. This fabrication-related effect is illustrated in Fig. 7(a) and is shown at the edge of a prototype image mapper cut by using tool 2.

The dark shaded regions in Fig. 7(a) indicate where the additional material is removed as a result of the included angle of the tool. Edge eating is most significant at the sides of the image mapper where the height difference between adjacent y-tilt facets is greatest. The edge eating effect is less significant for larger mirror facets; however, for smaller facets it can become quite dramatic, reducing the surface area of the facets by over 60% at the edges as demonstrated in Fig. 7(b). Edge eating decreases the throughput of the system and also the image contrast.

C. Edge Eating Reduction

The design of the image mapper must be optimized for the surface-shaped tool geometry to minimize the edge eating effect. This is accomplished three ways: first, the y tilts are staggered to minimize the step height difference between neighboring facets. Figure 8(a) shows a nonoptimized configuration with a large step height difference between repeating blocks of y-tilt-only mirror facets. Figure 8(b) shows the improved configuration in which the y tilts are staggered to minimize the step height difference of the repeating blocks.

Second, the x tilts are grouped on the y tilts, which decreases the edge eating effect by 4 $\times$, affecting only the first and fifth x-tilt facets. Figure 9(a) shows an example of a staggered y-tilt design but with no grouping of the x tilts. In this configuration, every facet experiences some edge eating effect. In contrast, by grouping the x tilts [Fig. 9(b)] on the y tilts, the total number of facets with edge eating is significantly decreased.

Third, the orientation of the x tilts in a concave (Fig. 10) profile as opposed to other orientations (convex) further reduces the effects of edge eating.

D. Fabrication Setup and Machining Parameters

For fabrication of the image mappers a high-precision CNC four-axis diamond lathe (Nanotech 250UPL) is used. This machine has 200 mm of travel for each axis (X , Y , Z) with nanometer-level precision. The workpiece is mounted on two stages with Y and Z -axis movement, while the spindle and diamond tool are mounted on the X -axis stage; see Fig. 11(a). The mirror facets are cut by moving the workpiece up and down on the Y axis. Tilts in the Y direction are achieved by moving in both the X and the Y directions while cutting each facet. After cutting a facet the spindle and tool move away from the workpiece, rewind, and begin cutting the next facet. The workpiece also steps over on the z axis by the tool width prior to cutting the next facet. The x tilts are obtained by mounting the workpiece to a goniometer with its cutting surface coincident with the goniometer's axis of rotation; see Fig. 11(b).

Because of the manual rotation of the goniometer, x tilts are fabricated at the same time. When one is finished, the operator adjusts the goniometer to the next x tilt, and the process is repeated until all mirror facets are fabricated. Y -height compensation factors are applied for the different x tilts. For large x -tilt angles, z -axis compensation factors are also used to compensate for the cosine effect.

The cutting parameters for the image mapper are listed in Table 3. In general, a rough cut is performed initially to get the different mirror facets into the aluminum substrate. After this step, a fine cutting program is used to clean up the image mapper, producing the best surface roughness and removing cosmetic imperfections such as metal flaps, chips, and other debris.

Figure 12(a) shows a picture of the final large-format (250 element) image mapper fabricated by using tool 3. Figure 12(b) shows a close-up side view of the image mapper, showing the excellent alignment of the facets. The x -tilt grouping and concave orientation are easily observed as well as the staggered y tilts.

4. Image Mapper Characterization

A. Geometric Errors

The mirror facet tilts and widths are measured by using a white-light interferometer (Zygo New View). Before component testing, the image mapper is placed on the interferometer's motorized four-axis stage (X , Y , θ_x , θ_y) and adjusted to align the reflected light from the zero tilt (x - and y -axis) mirror facet of the image mapper with the optical axis of the system. Any residual tilt is recorded and subtracted from the other facet tilt measurements. A 10 $\times$ Mirau objective with a 1.0 $\times$ field lens is used to collect the data. Ten measurements were taken for each tilt position and averaged together. Table 4 shows the final results, comparing the measured values to the designed values.

The results from this study demonstrate an excellent agreement between the ideal designed-for tilt values and those actually measured. The largest tilt error was -2 mrad for the x tilt ($\alpha_2 = 0.010$ rad) with most of the tilts having errors of less than 1 mrad.

Next, the width of each facet was measured by taking a cross-section profile across its surface at the left, center, and right edge of the facet. Figure 13 shows typical results obtained from these measurements. During the fabrication process, a 5 μm overlap was introduced to remove a thin metal flap between adjacent facets. This overlap changes the designed width of the facets from 75 μm to between 70 μm and 65 μm depending on facet position. For the center x tilts (2–4) the measured widths are within ± 1 μm of the 70 μm ; however, for the edge-positioned

x tilts (1 and 5) this changes from 50 to 70 μm depending on the y tilt. The highest facet due to the y tilt will be the thinner because of this overlap as well as some edge eating; this is shown in the 2D intensity maps in Fig. 13.

B. Surface Form Errors

In the development of the image mapper, each mirror facet is designed to be flat with no optical power. However, owing to imperfections in the cutting tools, the actual surface has some form errors across the facet width direction. These errors add optical power to the reflecting surface that alters the shape of the grouped pupils. For the large-format image mapper fabricated by using tool 3 there is a depression (depth $\sim 0.24 \mu\text{m}$) on the left-hand side of the facet (see Fig 14). Light reflected from the right-hand edge (length $\sim 15 \mu\text{m}$) of this region will broaden the pupil on one side, forming a comet shape.

C. Roughness Errors

The roughness of the mirror facet surfaces reduces the final image contrast and throughput of the image mapper. To quantify this effect, we used a white-light interferometer with a $50\times$ Mirau objective and $2.0\times$ field lens. Figure 15 shows a typical roughness result obtained from a single facet. For this fabrication method, the tool imperfections create lines along the length of the facets.

To gain a more statistical estimate of the image mapper's surface roughness, ten randomly selected facet surface regions were measured and found to have an average rms roughness of $5.3 \pm 1.2 \text{ nm}$. This value is similar to that previously reported by Gao [9] for the larger facets ($160 \mu\text{m}$ wide) and those reported by astronomical groups using other diamond machining techniques. The optical throughput of the image mapper is estimated by using an approach similar to the one reported by Dubbeldam and Robertson [12], where it is assumed that the image mapper's throughput is dependant only on the total integrated scatter from the mirror facet's surface and material reflectivity:

$$\eta(\lambda) = R(\lambda) \left[1 - \left(\frac{4\pi\bar{\sigma}_{\text{RMS}}}{\lambda} \right)^2 \right], \quad (9)$$

where $\bar{\sigma}_{\text{RMS}}$ is the average rms surface roughness and $R(\lambda = 500 \text{ nm}) \sim 99\%$ (aluminum substrate) is assumed for the entire visible spectrum. The image mapper's throughput, η , is estimated to be $\sim 97\%$, which is still high compared with other snapshot techniques [19,20].

5. Image Mapper System Level Tests

The final test for the large-format image mapper is to examine its ability to redirect light from similarly tilted facets to specific regions in the pupil. The ideal image mapper would create a high-contrast pupil image with low scattered light between the separate subpupils and sufficient spacing between the pupils to avoid overlap due to diffraction effects. A $4-f$ system test setup was constructed by using a large-FOV, high-NA objective as the collecting objective to evaluate the image mapper's performance. A schematic and actual picture of the test setup is shown in Figs. 16(a) and 16(b), respectively.

A green LED ($\lambda_D = 530 \text{ nm}$) and diffuser provide uniform incoherent illumination for the setup. Light from this source is then collimated by a collimating lens and refocused on the image mapper by the collecting objective. An adjustable field stop is placed behind the diffuser to adjust the area illuminated on the image mapper. A $600 \mu\text{m}$ pinhole is used as the input pupil

(i.e., aperture stop) for the system. An image of the pinhole at the image mapper has a diameter of $183\text{ }\mu\text{m}$, which is sampled by the mirror facets above the Rayleigh criteria. Light reflected from the image mapper travels back through the collecting objective and is reflected out of the illumination path by a 45:55 pellicle beam splitter, forming the array of subpupils. The subpupil array is relayed onto a color CMOS camera by a telecentric 1:1, relay where it is digitally recorded. Figure 17(a) shows an image of the actual subpupil array. A simulation of a subpupil array produced by an ideal image mapper as described by Eq. (4) is shown in Fig. 17(b). As one can see, there are differences between the ideal and the experimental results. One of the major sources of this difference is the non-perfectly-flat shape of the facets as was assumed in the ideal model. Taking into account the surface form error, an as-fabricated model was developed as shown in Fig. 17(c). This subpupil array has a much better correlation to the experimental subpupil array. To model the surface form error, two second-order polynomials were fitted to the white-light interferometer data shown in Fig. 14(b). One polynomial was fitted to the first region of the facet (0–0.010 mm) and the other polynomial was fitted to the second region (0.010–0.055 mm). The entire surface form error and the white-light interferometer data used to generate the surface are shown in Fig. 17(d). Cross-section profiles in both the y and x axes for both models and the experimental results are shown in Figs. 17(e) and 17(f), respectively. For the y axis, the theoretical and experimental results have excellent agreement with both the pupil diameters and the locations. In the x axis [Fig. 17(d)] the pupil locations are also in good agreement with the model; however, the experimental cross talk is still higher than the as-fabricated model, which predicts a new cross talk level of $\sim 5.4\%$. This increase is most likely due to other fabrication-related imperfections such as facet width variations due to edge eating and tool overlap and facet surface roughness. It is interesting to note that the model generated a similar asymmetric distribution of light in the pupil as is observed in the experimental results. This suggests that the surface form contributes significantly to this effect. In addition, the individual pupils have also become more elongated because of the surface form error, which is also present in the experimental results.

To quantify the amount of cross talk between the different subpupils generated by the real image mapper, the test setup in Fig. 16 was modified. The 1:1 relay was replaced with a 1:4 relay to increase the size of the pupil, making it easier to align, and an aperture using an adjustable iris. A lens with $f = 100\text{ mm}$ was placed right behind the iris to form a subimage of the image mapper. This subimage contains only light from mirror facets with no tilt in either the x or the y direction (0,0 tilt). This position was chosen because it contains the largest amount of cross talk and should be a worst-case scenario. Figure 18(a) shows a close up of two (0,0 tilt) mirror facets. An irradiance cross-section profile through the bottom mirror facet is displayed in Fig. 18(b) along with the theoretical cross-section profile. The difference between the two curves is assumed to be caused primarily by cross talk from neighboring facets. This cross talk is estimated by the ratio of the areas under the cross-section profiles and is found to be $\sim 10\%$, which is higher than the designed value of 1% but much closer to the as-fabricated model, which predicted a value of $\sim 5\%$. Note this value is the total contribution from neighboring facets on either side of the primary facet. It is assumed that this cross talk is consistent over the entire subimage, although further testing is still required.

Significant work has been undertaken to minimize the effects of cross talk between adjacent subimaging systems. There are two main reasons for removing cross talk in the system: the first is that cross talk will reduce the dynamic range, making it less sensitive to low-light objects, and the second is that cross talk will create inaccuracies in the spectral information. For our current level of cross talk ($\sim 10\%$) we anticipate a worst-case reduction in our dynamic range from 12 to 11 bits, which for most biological applications should still be sufficient. The reduction in the quality of our spectral information will require an additional software calibration step that takes into account the spectral dependence of the cross talk for each subimage. Although this calibration process may be time consuming, it is possible and can be

implemented with our existing system. Future work will continue to improve the quality of the individual facets in the image mapper to achieve our designed cross talk of 1%. We believe the majority of this cross talk is currently due to the surface form error in the facet; however, scattering from the facet surfaces and edges may also contribute to the system and will be further explored in the future. We are also actively working on developing a more advanced calibration procedure to help minimize the effects from cross talk that may exist in future systems.

6. Conclusion

In conclusion, this paper presents a new design and fabrication approach for making compact large-format image mappers. The design approach incorporates a multiple-tilt (x - and y -axis) geometry that can be efficiently grouped within a single collecting objective pupil. Because of the compact nature of the image mapper design, diffraction effects were considered and the design optimized for $\sim 1\%$ cross talk between adjacent pupils. The unique image mapper geometry was then fabricated by using surface-shaped diamond tools used in raster fly cutting mode on a precision four-axis diamond turning machine. This fabrication technique was developed specifically for creating large-format image mappers, as it significantly reduces the fabrication time and makes it possible to create these miniature features. To prove the new design and fabrication methods a 250 element, 25 tilt ($5x$ tilts, $5 Y$ tilts) image mapper was fabricated and tested at the component and system level. The geometric accuracy of the image mapper was measured to be <1 mrad for both x and y directions, which is acceptable for our design. Surface roughness for the individual facets was also acceptable for diamond machining techniques, with an average roughness of 5.3 nm. This roughness is estimated to decrease the throughput of the image mapper to $\sim 97\%$, which is still high compared with other techniques. Ongoing improvements are still required for the surface form of the mirror facets. Depressions in the mirror facets caused by diamond tool flatness errors are creating additional cross talk between the pupils. Tools with better flatness and slightly wider ($+5 \mu\text{m}$) are expected to get our cross talk down to the designed level of 1%. Software calibration procedures may also be used to remove residual cross talk in the IMS system; however, dynamic range will be reduced. We are currently exploring new tool fabrication methods such as ion beam etching to get better surface-quality tools for the image mapper.

In the future these large-format (≥ 250 element) image mappers will be incorporated into a high-resolution IMS fluorescence microscope and/or other biomedical imaging devices. Diffraction effects are also being explored for improving the spectral and/or spatial sampling of the system in addition to minimizing cross talk between subpupils. This work is supported by the National Institutes of Health under grants R21EB009186 and R01CA124319.

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Fig. 1. (Color online) (a) Basic configuration for the IMS system. (b) Illustration of the mapped final image on the detector prior to dispersion. (c) Close up of subimage 2 with dispersion of the linear mappings.

Fig. 2. Minimum collecting objective pupil size for the grouped pupil array based on (a) geometric and (b) diffraction models. Pupils in (a) and (b) are not drawn to scale.

Fig. 3.
Theoretical pupil diffraction model.

Fig. 4.

(a) Simulated irradiance at a single subpupil created by diffraction at the image mapper. (b) Irradiance from one pupil entering a neighboring subpupil (defined as cross talk).

Fig. 5.

(a) Front view for fabrication of an image mapper using diamond raster fly cutting technique.

(b) Top view of an image mapper during fabrication. The close up shows the diamond tool cutting the facet profile into the workpiece.

Fig. 6.

(a) Drawing of a flat bottom surface-shaped tool for fabrication of the image mapper with some of its critical design parameters labeled. (b) Actual fabricated tool with a $75\ \mu\text{m}$ wide flat bottom profile at the tip of the tool. The location of the rake angle, β , is also shown in this picture.

(a)

(b)

Fig. 7. (Color online) (a) Illustration of the edge eating effect due to the y-tilt height differences at the edge of the image mapper. The shaded regions indicate where excess material is removed. (b) Image of an actual prototype image mapper with obvious edge eating on mirror facet 5.

Fig. 8.

(a) Nonoptimized sequential y-tilt layout with large y-tilt height difference, h . (b) Optimized staggered y-tilt image mapper layout with minimum y- height difference.

(a)

(b)

Fig. 9.

(a) Nongrouped x tilts, illustrating an increased edge eating effect. (b) Grouped x tilts (A, B, C, D, E) on each y tilt (1, 2, 3, 4, 5). Edge eating occurs at only the boundary between x tilts A and E.

Fig. 10. Concave distribution of x tilts further reduces the effect of edge eating at the interface regions between y tilts.

Fig. 11. (a) Picture of Nanotech 250 UPL machine with axes labeled. (b) Close up of goniometer fixture used to rotate the image mapper for fabrication of x -tilt mirror facets.

(a)

(b)

Fig. 12.

(a) Actual picture of the large-format image mapper (250 mirror facets) next to a US Quarter for size comparison. (b) Close up side view of the image mapper showing the excellent alignment of the facets.

Fig. 13.
(Color online) White-light interferometer surface profile measurements of the individual mirror facets in the large-format image mapper taken at the (a) left edge, (b) center, (c) right edge of the component.

(a)

(b)

Fig. 14.

(Color online) Facet surface error in facet width direction. (a) Single facet white-light interferometer image under 50 $\times$ objective, 1.3 $\times$ field lens. (b) Cross-section profile for the facet in (a).

Fig. 15.
(Color online) Typical roughness results obtained from a large-format image mapper fabricated using a $75\ \mu\text{m}$ wide surface-shaped diamond tool.

Fig. 16.

Test setup for imaging the pupil after reflection from the image mapper, (a) schematic drawing, (b) labeled picture of the actual setup. B.S., beam splitter.

Fig. 17.

Grouped subpupil array comparison between measured and theoretical results: (a) experimental image of the grouped pupils, (b) ideal model, (c) as-fabricated model incorporating the surface form error described in Subsection 4.B. (d) Curve fit of the surface form error used in part (c). Cross sections from both models and experimental results on the (e) x axis and (f) y axis.

Fig. 18. (Color online) (a) Close up image of the image mapper from the center pupil with only (0,0) tilts for (x, y) . (b) Cross-section irradiance profile of the top facet showing ~10% cross talk from the neighboring facet.

Table 1

Large-Format Image Mapper Design Parameters

Parameter	Value
Length, l	20 mm
Width, w	20 mm
Mirror facet width, b	75 μm
No. of x -tilt angles, L_x	5
No. of y -tilt angles, L_y	5
x -tilt magnitude, α_j	0.02 rad
y -tilt magnitude, β_k	0.04 rad
$\text{NA}_{\text{mapper}}$	0.004
$\text{NA}_{\text{COLLECT}}$	0.150
Material	Kobe Al

Table 2

Surface-Shaped Flat Bottom Tool Design Parameters

Parameter	Tool 1	Tool 2	Tool 3
Included angle, θ , (deg)	20 ± 0.5	20 ± 0.5	5 ± 0.5
Side clearance angle, α (deg)	3	3	3
Tip clearance angle, ϕ (deg)	6	5	5
Top rake angle, β (deg)	0	0	0
Tool tip width (μm)	150 ± 15	70 ± 7	70 ± 7
Max. depth of cut (μm)	500	300	300
Edge quality	750x	750x	750x
Material (diamond)	Synthetic	Synthetic	Synthetic

Table 3

Cutting Parameters for Image Mapper

Parameter	Rough Cut	Final Cut
Feed rate (mm/ min)	30	30
Depth of cut (μm)	40	5
Spindle speed (rev/ min)	2800	2800
No. of passes	11	1

Table 4

Comparison of Image Mapper Tilt Designed and Measured Values

x Tilt (α)	y Tilt (β)	Ideal (rad)	Measured		Error	
			(α)	(β)	(α)	(β)
α_1	β_1	+0.020	+0.020	+0.020	0	0
α_2	β_2	+0.010	+0.098	+0.010	-0.002	0
α_3	β_3	0	—	—	—	—
α_4	β_4	-0.010	-0.010	-0.010	0	0
α_5	β_5	-0.020	-0.021	-0.020	+0.001	0