Imaging with microlenslet arrays

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1. ABSTRACT

Recent investigation demonstrated the feasibility of using stacks of microlenslet arrays for optical imaging applications. Many applications driving our research require ultra-compact magnifying imaging systems. In this investigation we demonstrate that a magnifying system based on a stack of two dissimilar microlenslet arrays is feasible.

2. INTRODUCTION

Many applications require integration of an ultra-compact magnifying optical system incorporated into another optical system. For example, a driving application for our research comprises of magnification of miniature displays in head-mounted displays (HMDs).[1] An example of such integration is illustrated in Fig. 1 for a recently conceived HMD.[2]

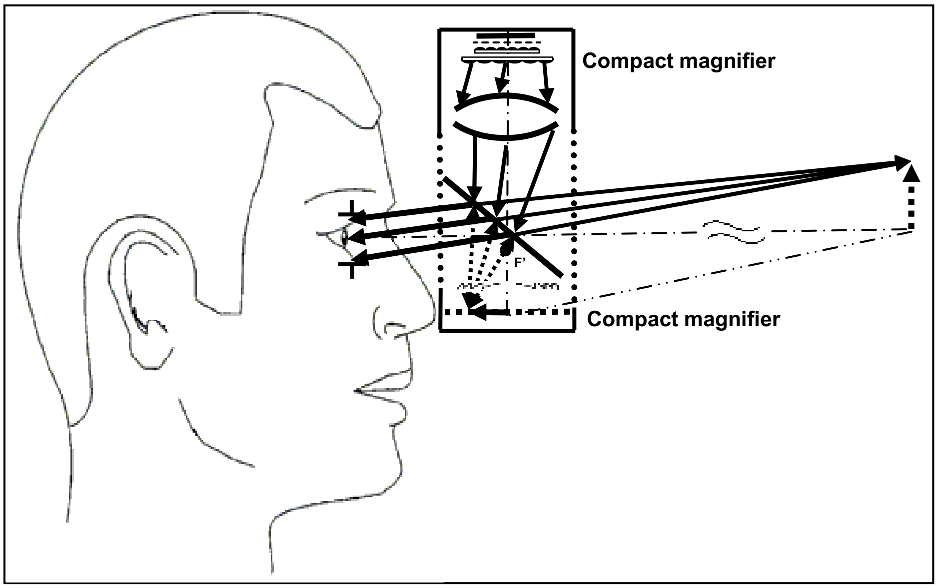


Figure 1. Conceptual design layout of a see-through HMD with integrated compact magnifier.

In such configuration, magnification of the miniature display is needed to minimize the overall length of the optical assembly to further increase the field of view (FOV) of the HMD. Furthermore, another compact lens, such as a Fresnel lens, is required to image the phase conjugate material (PCM) at, or approximately near, the virtual image plane directly in front of the user's line of sight. Given the compactness requirements imposed on any HMD system, a magnifying system with a size and weight of a few millimeters and a few grams, respectively, are desired. Another application driving our research and requiring compact magnifying systems is in the field of optically created special effects, where an intermediary image plane is formed by an objective lens. The intermediary image is further altered by an optical phase plate to create optical painterly effects. The altered image is consequently relayed to the final image plane where a recording device is located.[3] As part of our previous work, we designed a state-of-the-art 1:2 magnifying system, however while compact, this system still had an overall object to image length (OAL) of 120mm and weights over 700 grams.[4] Therefore an alternative approach had to be investigated. Optical magnifying systems based on microlenslet arrays could provide a useful solution for such applications.

The basic theory of imaging with microlenslet arrays, developed by R.H. Anderson, was driven by requirements of optical scanning devices.[5] In his work, Anderson demonstrated that arrays of simple lenses combined with appropriate baffles could be used in close-up imaging systems for black and white document copiers, oscilloscope cameras, as well as binary code scanners. Microlenslet-array based imaging systems were consequently further investigated for optical scanners and copiers,[6,7] and 3D integral photography.[8] The imaging capabilities of microlenslet arrays for either grayscale or color images were previously investigated, and it was demonstrated that 1:1 compact relays for such images could be conceived with OAL of less than 7mm.[9]

3. OPTICAL LAYOUT OF MICROLENSLET-ARRAY BASED MAGNIFYING SYSTEM

There are many possible configurations that can be used to create an optical 1:2 magnifying system with a stack of two dissimilar microlenslet arrays, respectively.[10] Let's consider the general configuration shown in Fig. 2

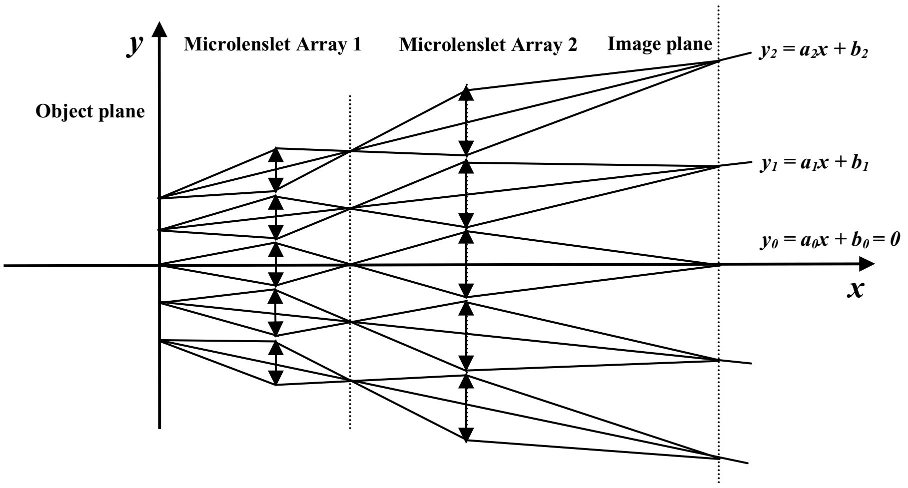


Figure 2 First order optical layout of a magnifying system comprising a stack of two dissimilar microlenslet arrays.

In this configuration the first and the second microlenslet arrays are of focal lengths f_1 and f_2, of diameters D_1 and D_2, and operate at magnifications of m_1 and m_2, respectively. The overall magnification of such system is $M=m_1m_2$. The equation describing each optical sub-axis, defined as the axis through the centers of the *i-th* lenslet pairs, for $i=1,2,\ldots.n$, is given by

$$y_i = a_i x + b_i \ , \tag{1}$$

where a_i and b_i are the tilt and the offset for each optical sub-axis, respectively. Furthermore, it can be shown that for the special case of 1:2 magnifying system, each optical sub-axis in Eq. (1) reduces to

$$y_i = (2ia)x + b \, , \tag{2}$$

where a and b are given by

$$a = \frac{D_2 - D_1}{d} \ , \tag{3}$$

$$b = \left(\frac{D_2 - D_1}{d}\right) OAL \, . \tag{4}$$

Eq.(2)-(4) are sufficient to describe the geometrical relationships between the two imaging microlenslet arrays and the object and image planes. To assess the feasibility of the magnifying device shown in Fig. 2, MATLAB code was developed to compute the exact geometrical parameters for a given optical configuration.

Two key aspects of imaging with stacks of microlenslet arrays are ghost images and lensletization that lead to first order image degradation. A stack of microbaffles placed at the location of the entrance pupil was used to eliminate the ghost image formation in the system. In addition, enough overlap among the sub-fields of view of each microlenslet pair was secured to minimize the lensletization.[9] The final optical layout of the investigated system is shown in Fig. 3

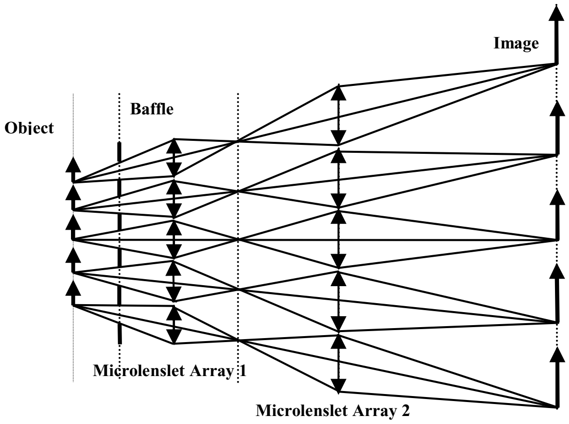


Figure 3 Microlenslet array based optical magnifying system with appropriate baffle.

4. THEORETICAL MODELING

In order to further analyze the imaging properties of microlenslet array based magnifiers, a computer model was developed using custom-designed software based on the ASAP^{TM}. The first aspect of modeling is to define an appropriate light source or equivalently an object to be imaged. A complex grayscale light source, such as a bitmap portrait, was selected to assess the grayscale imaging capability of the proposed microlenslet array based magnifier. In the case of grayscale images, image quality may be assessed subjectively as well as with more sophisticated quantitative approaches.[9]

The optical layout of a 1:2 system using two arrays of each 9 by 9 microlenses, combined with an associated baffle located at the entrance pupil of the system is shown in Fig 4.

Moreover, each lens in the first array was an F/5 square plano-convex lens, of 0.15mm thickness, and 500µm focal length. Each lens in the second array was an F/8.3 square plano-convex lens, of 0.15mm thickness, and 1000µm focal length. Because we use simple plano-convex singlets to establish feasibility, which inherently have significant axial chromatic aberration, we only consider imaging single color grayscale image, which we selected without loss of generality to be λ equal 656nm.

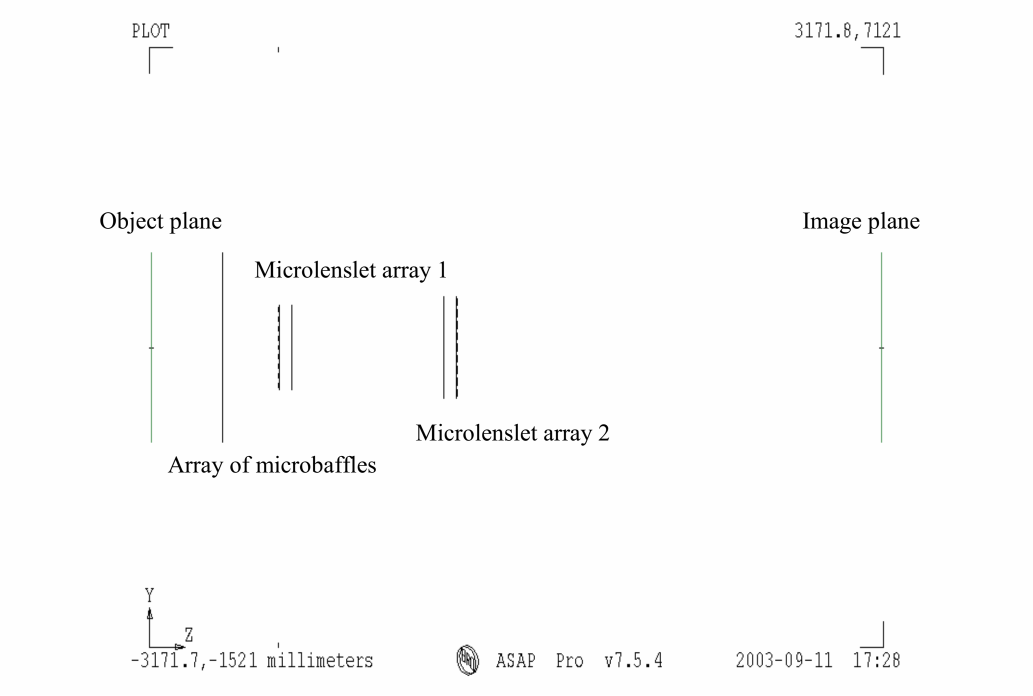
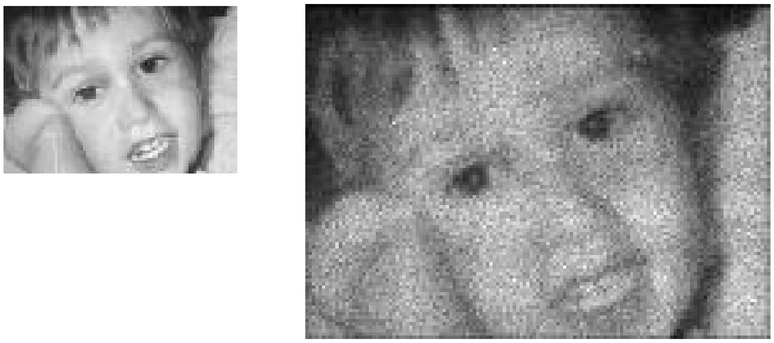


Figure 4 ASAP^{TM} model of microlenslet array magnifying system.

In our previous work we demonstrated that one level of optimization in optical raytracing is to direct the rays towards the entrance pupil of the optical system. While in the case of microlenslet arrays no single pupil exists but instead many sub-pupils must be considered, a fictitious pupil is defined that encompasses all the sub-pupils. Building on this scattering technique, which is standard in ASAP^{TM} software, the raytrace was further optimized. The rays were first traced from the source to the diffuser, and then only the scattered rays were traced from the diffuser towards the fictitious entrance pupil of the system. An analysis of the minimum number of rays to achieve 95% accuracy, which is enough for a first order feasibility assessment, demonstrated that a total of 100 million rays traced through the system is sufficient.[11] Results of feasibility simulations using a grayscale light source and 100 million rays are shown in Fig. 5 for the imaging configuration shown in Fig. 4.



(a) **(b)**

Figure 5 Simulation of imaging of a grayscale object through a stack of two dissimilar microlenslet arrays: (a) a grayscale object and (b) image through the system.

Furthermore, to assess the potential image quality of the proposed imaging system if more rays were traced, the imaging performance was evaluated for the central wavelength in terms of the modulation transfer function (MTF) for the on axis pair of microlenses (i.e. the pair of microlenses with optical sub-axis described by $y=0$). Fig. 6 demonstrates the monochromatic diffraction MTF for up to 50% vignetted FOV, presented across five representative field angles. By evaluating the performance of the investigated system we need to satisfy a criterion of 20% modulation in the case of magnifying a miniature display in an HMD. In the unoptimized system presented in this paper for feasibility study, the results of the MFT plot illustrate a spatial frequency of 4cycles/mm at 20% modulation.

5. CONCLUSION AND FUTURE WORK

Results presented in this paper demonstrate that an ultra-compact magnification system based on a stack of two dissimilar microlenslet arrays can be designed since a final image with no apparent ghosting or lensletization can be formed. In future work, we will investigate the relationships describing the optical parameters of the microlenslet array-based magnifying system and will optimize the proposed configuration to satisfy the criteria for maximum compactness with no ghosting or lensletization. Also, we will investigate the higher order image properties of such systems and will optimize the system accordingly. As part of our driving applications in HMDs we will need to optimize the performance of the imaging system to satisfy a spatial frequency of approximately 24cycles/mm to drive 0.6 inch 800x600 miniature displays.

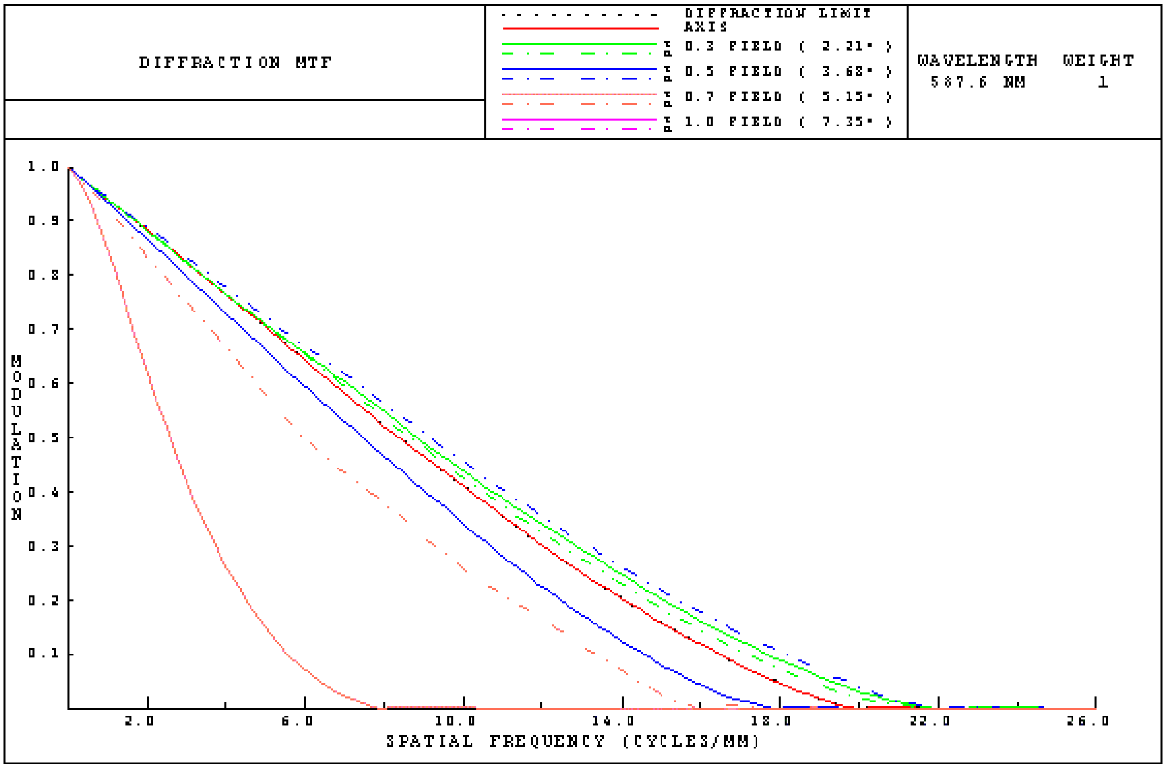


Figure 6 Chromatic diffraction MTF for microlenslet pair.

6. ACKNOWLEDGMENTS

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