Implementation of Adaptive Coded Aperture Imaging using a Digital Micro-Mirror Device for Defocus Deblurring

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***Abstract*—Digital image processing (DIP) and computational photography are ever growing fields with new focuses on coded aperture imaging and its real world applications. Traditional coded aperture imaging systems consisted of statically coded masks that were designed and constructed from cardboard or other opaque materials and could not be altered once their shape had been defined. This is undesirable as numerous aperture pattern masks exist, each with their own advantages and disadvantages, and alternating between aperture shapes with a traditional camera quickly and efficiently is impractical. This paper aims towards developing an adaptive coded aperture imaging system utilizing a digital micro-mirror device (DMD) as a programmable aperture that is able to switch between different aperture patterns quickly and efficiently. This provides all the advantages of traditional coded aperture imaging systems but without the disadvantage of having a static aperture in the aperture plane.**

I. Introduction

Digital image processing (DIP) has very wide applications in numerous environments and almost every technical field today is impacted, either directly or indirectly, by digital image processing. Associated closely with the field of DIP is computational photography, a field of research that comprises of techniques in computational imaging to improve images that are taken as a result of digital photography. Computational photography is a highly interdisciplinary field which utilizes concepts and principles from engineering, physics, optics, mathematics, computer vision and image processing.

Although many techniques exist that allow for one to optically code images, the focus of this paper is developing a coded aperture imaging system with a programmable aperture mask that exhibits all the advantages of conventional coded aperture systems but without the disadvantage of having a statically coded aperture mask. While many applications of coded apertures exist, this paper focuses only on defocus deblurring, which is the attempt to recover a sharp, in-focus image from a blurred one. The scope of this work includes analysing the current pitfalls of conventional statically coded aperture masks and determining the viability of having a programmable mask technology in the aperture plane of an imaging system. Previous attempts to introduce a dynamically programmable aperture into an imaging system has led to poor image quality and thus poor results. This paper aims to address these issues and provide a more viable programmable aperture technology that offers better quality images.

The next section, Section II gives the background to development of the adaptive coded aperture imaging system. This is then followed by an overview of related work in Section III. Section IV details the design and implementation of the required system using hardware and software available. Section V details the results obtained after the system was developed and Section VI presents the concluding remarks as well as the future work that could be implemented to the system.

II. Background

In a world that is 3-dimensional in nature, traditional photography captures only 2 dimensions, that means that a great detail of information is lost. Digital cameras today have limited depth of field (DOF) and thus the parts of the image away from the plane of focus appear blurred. Using advanced camera systems, i.e. complex optics and electronics, allows one to capture an all-focus image, i.e. one that has a large DOF for the purposes of, for example, tracking.

One of the ways used to deblur an out of focus image is the use of a coded aperture mask which is usually inserted into the aperture plane of a lens or camera system. This patterned occluder alters the incident light so that the image captured by the sensor is not the final desired image but is coded to facilitate the extraction of more information than if it had not been coded at all. Coded aperture imaging has been around for several years, with coded masks developed from static materials that often cannot be changed once a pattern is encoded onto them. This is undesirable and thus implementing dynamic aperture masks that can be programmed to change shape is advantageous. It opens up a

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whole new range of possibilities in coded aperture imaging such as being able to test aperture mask shapes that could previously not be constructed using conventional cardboard methods.

Many different technologies available today could be used as programmable apertures but this paper will investigate the use of a digital micro-mirror device (DMD) as a potential aperture mask. Digital micro-mirror devices are small electromechanical devices that consist of programmable arrays of individual microscopic mirrors that can steer light in any one of two directions depending on the tilt of the mirrors.

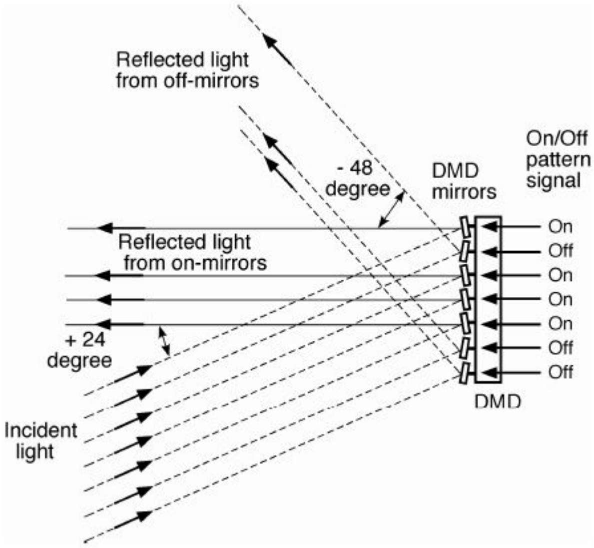


Fig. 1: Digital micro-mirror device reflecting rays of incident light in different directions [1].

Figure 1 illustrates incident light being reflected in one of two directions by each of the DMD mirrors. These devices can act as excellent spatial light modulators and thus the viability of using a DMD as a programmable aperture mask in an imaging system will be established.

III. Related Work

This section details an overview of existing research related to the fields of digital image processing, coded apertures and computational photography. A brief summary is given into a selection of related work to provide a context for our development.

Research in coded apertures has been ongoing for the past decade, with coded aperture masks shown to be far superior to traditional aperture masks in defocus deblurring and depth estimation. In Levin et al. [2], a novel aperture mask was developed to better extract depth from a single coded image. This was done using a conventional camera and lens with a coded mask cut out from cardboard and inserted into the aperture plane of the lens. A novel deconvolution algorithm was also developed to better deblur an out-of-focus image based on natural image priors. The problem with this implementation was that the aperture pattern used for defocus deblurring could not be used for depth estimation as a single mask cannot be optimized for both [3]. This means that each mask would have to be inserted individually which is time consuming and impractical in a real world application. Thus a programmable aperture mask would be advantageous.

Programmable masks have been used before but, due to their nature and technology, often produce worse images and results than conventional static masks. In Choi et al. [4], a liquid crystal array (LCA) was used as a transmissive coded aperture mask to allow for depth sensing from a conventional camera. The application was successful but the image quality was poor, due to diffraction and light loss caused by the Liquid crystal technology, and thus could not be used. Nagahara et al. [5] constructed a programmable aperture camera using a liquid crystal on silicon (LCoS) as the adaptive mask. This technology is similar to the LCA but is reflective rather than transmissive. They also experienced poor images as the LCoS needs advanced optics to use as an aperture and thus the system could not be perfected. Clearly another technology is needed as the adaptive mask. Nayar et al. [6] made use of a DMD for spatio-temporal exposure variation and advanced dynamic ranging. The results they achieved with the DMD were notable and thus this device will be tested in a coded aperture application to determine its merit.

IV. Design and Implementation

There were several factors to consider before the adaptive coded aperture imaging system could be developed. This section details the design and development of the system.

A. Optical Design

In order to get the DMD to perform effectively as a coded aperture mask, one would need to get the DMD into the aperture plane of the camera or lens system. This is by no means a trivial task, as there are various factors to consider. The basic principal is to allow the DMD to control the amount of light energy that reaches the CCD without actually forming an image on the DMD itself. This is achieved by the use of lenses to collimate light from an object onto the DMD, which then directs light towards another lens that converges the light towards a charge coupled device (CCD) to capture the encoded image. Figure 2 illustrates how the DMD is introduced into the aperture plane of an imaging system.

This setup could effectively allow any pattern to be displayed on the DMD and the corresponding image to be captured by the CCD.

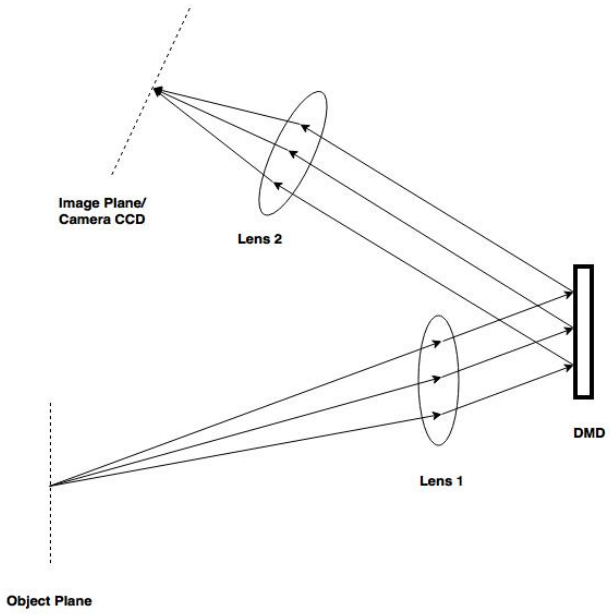


Fig. 2: DMD optical imaging setup.

B. Defocus Blur

Defocus blur can simply be modelled as the convolution between a sharp image and a point spread function (PSF). Mathematically,

$$f = x \otimes k + \phi, \tag{1}$$

where f denotes a blur image, x is a sharp, in-focus image and k represents a blur kernel or PSF and ϕ is the white Gaussian noise present, modelled by a $N(0, \sigma^2)$ distribution. We can take the Fourier transform of the above equation to get a frequency domain equivalent:

$$F = X \times K + \Phi, \tag{2}$$

where F, X, K and Φ are the Fourier transforms of f, x, k and ϕ respectively. We can see that the convolution in Equation 1 becomes multiplication in Equation 2, which is a standard property of the Fourier transform.

Figure 3 shows the power spectra of different aperture patterns with respect to a conventional circular aperture as computed by [7]. This was done by taking the Fourier transform of the PSF for the various aperture masks and comparing the results graphically. Circular apertures have lots of zero crossings in the Fourier domain and this leads to loss of information when multiplied with a sharp image. The coded aperture masks, however, have few zero crossings, which leads to the preservation of spatial information, and therefore makes the deblurring process easier.

C. Aperture Selection

To accurately determine if the optical configuration of the DMD coded camera is accurate and effective, a coded aperture

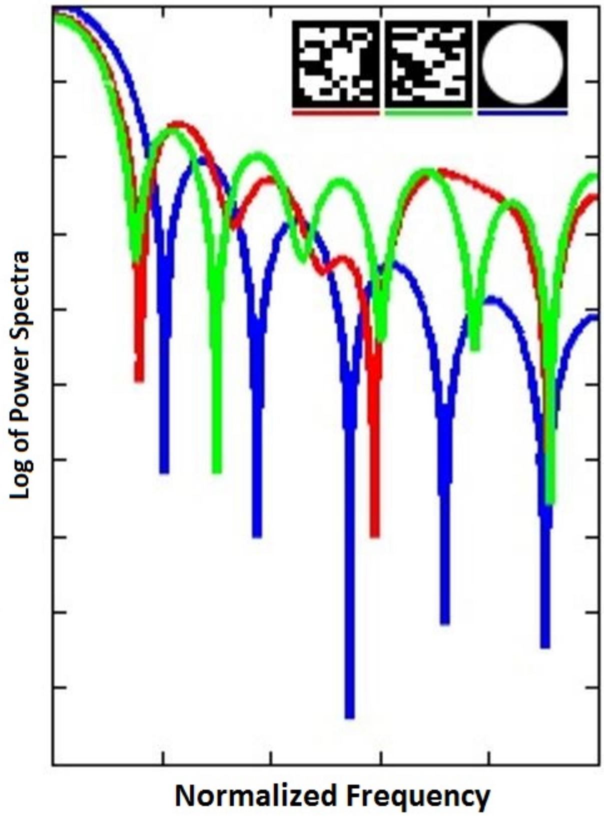


Fig. 3: Power Spectra comparison of different coded aperture patterns with respect to a circular aperture [7].

mask developed in Levin at al. [2] was selected and compared to that of a conventional circular aperture mask. It was shown in [2] that the coded mask developed was far superior to that of a conventional circular aperture in defocus deblurring. Thus if the results can be replicated using the developed DMD coded camera then indeed the optical configuration of the camera is correct. Figure 4 shows the difference in shape between the two aperture masks.

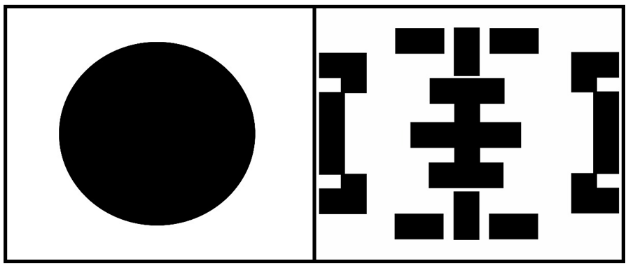


Fig. 4: Two aperture masks used in defocus deblurring experiment. (a) Conventional circular aperture. (b) Coded aperture developed by [2].

These masks were generated on the DMD and the resultant images were then captured and compared.

D. Defocus Deblurring

Since defocus blur can be seen simply as the convolution between a sharp image and a blur kernel, one can solve for the sharp image again by deconvolving the blurred image with the same point spread function used to blur the original sharp image. This PSF can simply be estimated using the camera and scene parameters and will resemble the shape of the aperture for objects out of the focal plane of the lens with the scale being a function of depth.

E. Hardware Considerations

The cost and the availability of the various components needed to implement the system played a big role in the final design. In the end, the system was implemented using two plano-convex lenses, a 1.3-mega-pixel monochrome camera and the Discovery D3000 kit which includes a 0.7" XGA digital light processing (DLP) device produced by Texas Instruments with a resolution of 1024 $\times$ 768. A DLP is essentially a DMD produced by Texas Instruments under a different name. These components were chosen either because they were cheap and easily available or already owned by the authors. This means that the components may not be the most suited for the design and thus the results achieved from this set-up would not be optimal.

V. Results

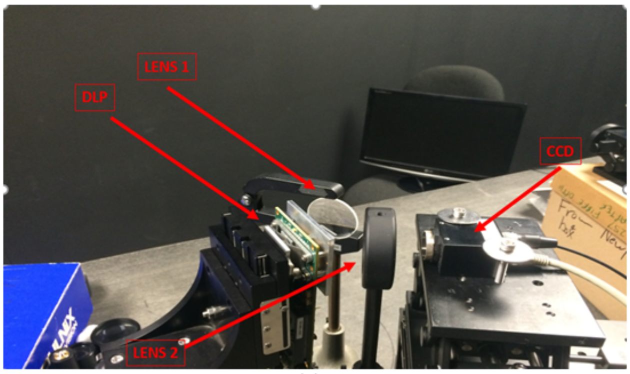
This section presents the results of the imaging system implemented and the outcomes obtained from the experiments performed.

A. System Configuration

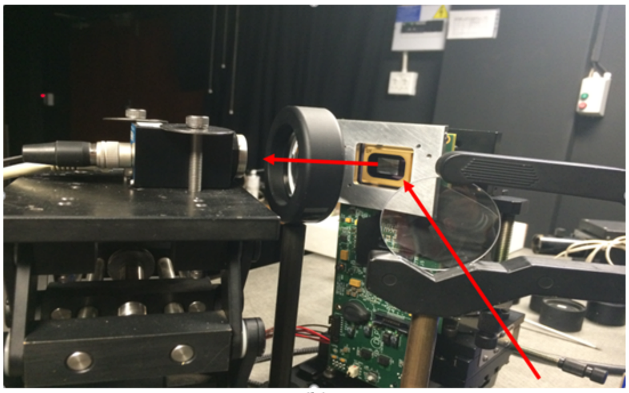
Using all the components as mentioned in section IV, a suitable DLP coded aperture camera was constructed that allowed for different aperture masks to be generated on the fly using the DLP. The resultant images could then be captured using the CCD camera. Figure 5 shows the layout of the various components in the design.

B. Defocus Deblurring Results

We can see the superiority of coded apertures compared to conventional circular apertures in defocus deblurring which is illustrated in Figure 6. Standard USAF 1951 and ISO 12233 resolution charts were displayed on a liquid crystal display (LCD) screen. Using the DLP coded camera, the images were captured using both a conventional circular aperture and a coded aperture developed by [2]. In Figure 6 (a) we see the raw image captured of the USAF 1951 chart using a circular aperture. In Figure 6 (b) we see the image deconvolved using a sparse prior algorithm developed by [2]. The result is an image with lots of ringing artefacts and minimal detail present. None of the vertical or horizontal bars are even slightly distinguishable from each other. However, in Figure 6 (c) we see the image captured using a coded aperture mask. Figure 6 (d) shows the image deconvolved but this time using the PSF of the coded mask. We see a much better deconvolved image, with less ringing and the vertical and horizontal bars being easily distinguishable from each other. Some of the numbers on the side of the image are more visible and readable as compared to the image in Figure 6 (b).



(a)



(b)

Fig. 5: DLP camera experimental setup. (a) Experimental setup with components labelled. (b) Direction of light rays travelling through system.

In Figure 7 (a) we see the raw image captured of the ISO 12233 chart using a circular aperture. The image is then deconvolved in Figure 7 (b). In Figure 7 (c) the same image is captured, this time using the coded mask. The deconvolved image is then shown in Figure 7 (d). We can see again that the coded mask is far superior to the conventional aperture for defocus deblurring as more detail and less ringing is present in the coded mask deconvolved image.

VI. Conclusion and Future Research

A. Summary of Results

From the results obtained, it is clear that coded apertures are far superior to circular apertures for defocus deblurring. The introduction of a DLP into the aperture plane of a camera system was very effective. It allowed for coded aperture masks to be generated via software, rather than by having different aperture patterns cut from cardboard and inserted into the

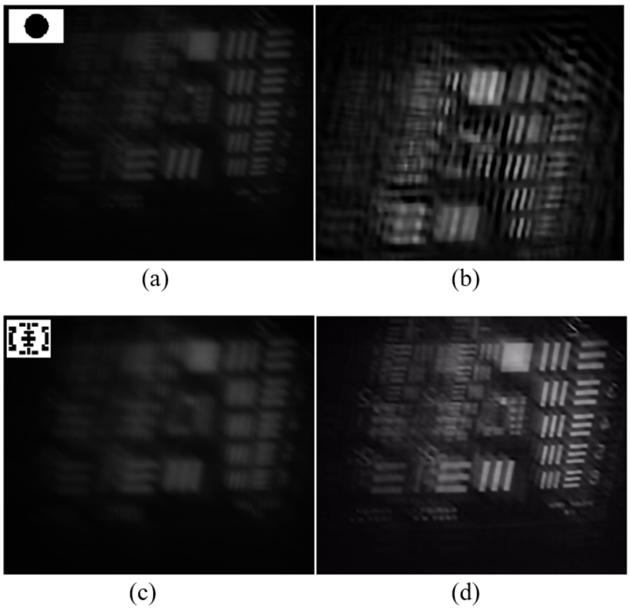


Fig. 6: USAF 1951 resolution chart deblur experiment. (a) Image captured using DLP camera with a circular aperture (shown top left of image). (b) Deconvolved image with circular aperture. (c) Image captured using DLP camera and coded aperture (shown top right). (d) Deconvolved image with coded aperture.

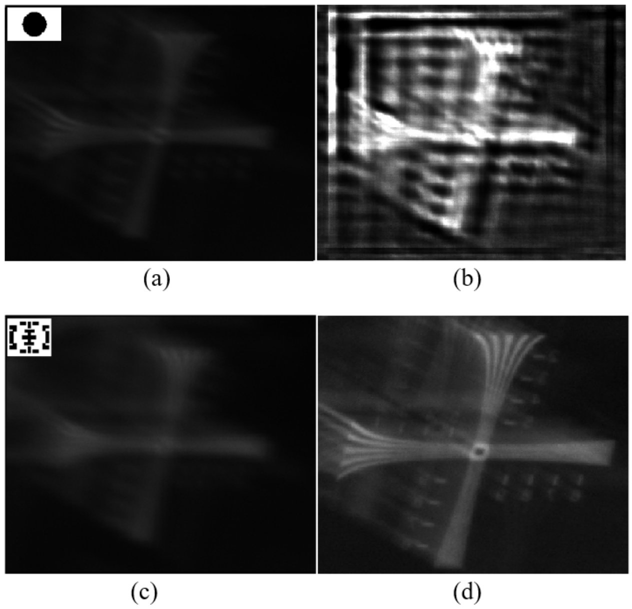


Fig. 7: ISO 12233 resolution chart deblur experiment. (a) Image captured using circular aperture. (b) Deconvolved image with circular aperture. (c) Image captured using coded aperture. (d) Deconvolved image with coded aperture.

aperture plane of a lens. Although the deconvolved images do contain a certain level of noise, notable amounts of detail in the coded aperture image can be recovered as compared to the circular aperture image. Clearly high frequency information was preserved using the coded aperture mask and the images contain less ringing and other artefacts. Thus the DLP is effective as an adaptive coded aperture mask.

B. Future Improvements

Although only one coded mask was compared to a conventional aperture, the use of the DLP opens up the possibility to test several hundred different aperture shapes and patterns. These masks will be tested in the future to evaluate their effectiveness for different imaging applications. Since the DLP has very high frame rates and could effectively generate hundreds of patterns each second, this opens up the possibility to test non-binary coded aperture patterns by modulating the light that reaches the CCD sensor. The experiments presented in this paper made use of plano-convex lenses to produce images, however, other lenses such as achromatic doublet lenses will be investigated to see if they offer any improvement to the image quality. Images captured were also generated on an LCD screen, and future work will involve photographing real scenes.

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