A Practical Enhanced-Resolution Integrated Optical-Digital Imaging Camera (PERIODIC)

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ABSTRACT

An integrated array computational imaging system, dubbed PERIODIC, is presented which is capable of exploiting a diverse variety of optical information including sub-pixel displacements, phase, polarization, intensity, and wavelength. Several applications of this technology will be presented including digital superresolution, enhanced dynamic range and multi-spectral imaging. Other applications include polarization based dehazing, extended depth of field and 3D imaging. The optical hardware system and software algorithms are described, and sample results are shown.

Keywords: Computational imaging, array imaging

1. INTRODUCTION

Even the best commercially available imaging systems employ a mere concatenation of individually optimized optical, sensor, digital processing, and visualization subsystems, with scant attention paid to the optimization of the overall system performance against the full panoply of system trade-offs. In the emerging paradigm of integrated imaging systems, the focus has slowly but surely begun to shift toward end-to-end optimized systems that maximize the information content of images relative to a set of prescribed imaging tasks. Digital post-processing is an essential ingredient of this approach. The design of the optical and detection subsystems is optimized for efficient information gathering; post-processing merely renders the gathered information in the most desirable form (e.g., visually most pleasing form) in the final image. Information is clearly the most important metric of integrated-imaging system performance. In the PERIODIC concept, illustrated in Figure 1, we employed an array of imaging channels combined with a set of diverse optical elements to maximize information content. Array imaging, rather akin to the function of compound eyes of insects like flies, is at the leading edge of the ongoing computational-imaging revolution. Multiple optical elements permit the use of a range of information gathering strategies in parallel that can turn what would otherwise be simple yet powerful digital imagers into comprehensive scene interrogators with multiple functionalities, such as high spatial and spectral resolution, high dynamic range, high depth and width of the field of view, excellent target recognition capabilities, and well optimized computational strategies that can employ data compression and fusion. In this project our specific goals were to develop theoretically, computationally and experimentally advanced systems for multi-modal computational array imaging systems that could:

- produce high resolution reconstructions from lower resolution sub-images
- enhance dynamic range
- extend depth-of-field and field-of-view over traditional imaging systems
- provide multi-spectral imaging data
- exploit polarization information for applications including dehazing
- be integrated into a thin form-factor imaging system using COTS components
- be implemented using special purpose computational platforms capable of being embedded into a small portable unit.

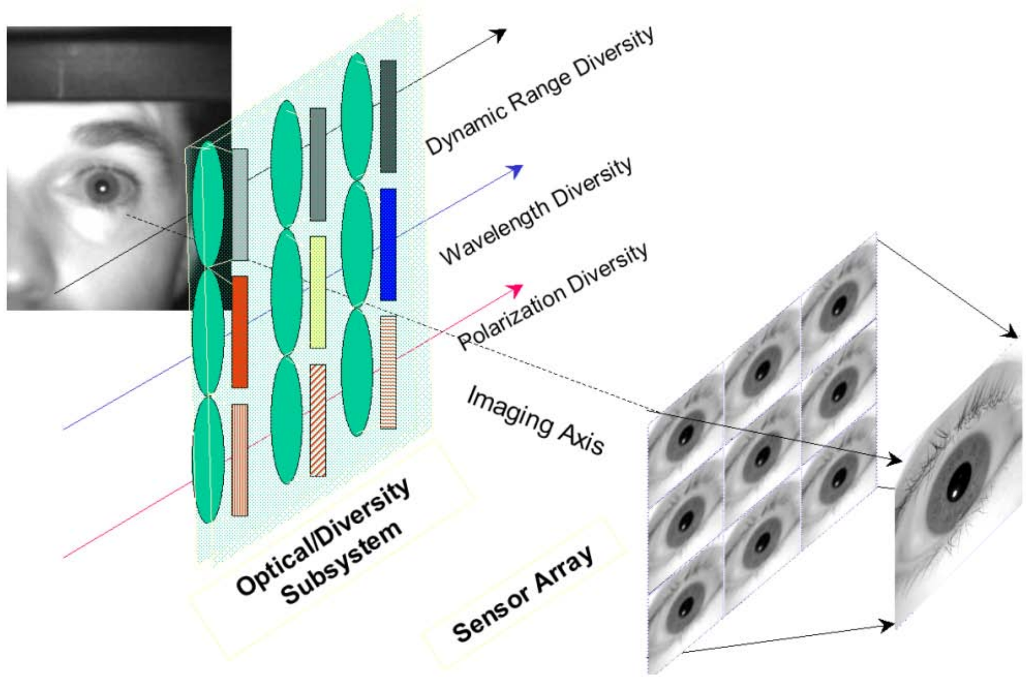

Figure 1. Illustration of the PERIODIC concept in which we employed an array of imaging channels combined with a set of diverse optical elements to maximize information content

2. HARDWARE PLATFORM

The PERIODIC prototype imaging system is based on a commercial-off-the-shelf, 10.7 mega-pixel, monochrome CCD camera, model Lw11059 (Luminera Inc. North Andover, MA, USA). The actual CCD chip is a model KAI-11002 (Kodak Rochester, NY, USA). The dimensions of the CCD are 36.1 mm by 24.0 mm (4008 pixels by 2672 pixels), with 9µm square pixels. The Luminera camera (CCD, electronics, and USB interface) are mounted in an aluminum housing that allows accurate positioning of the CCD relative to the optics and provides adequate air flow for cooling, while maintaining a relatively light-tight environment. A mounting bracket on the front of the camera housing allows repeatable positioning of the lens plate in close proximity to the CCD.

The lens plate consists of black anodized, aluminum plate with 18 tapped holes to accommodate 18 lens assemblies and is shown in Figure 2. Each lens assembly is a commercial-off-the-shelf, multi-element, glass lens system enclosed in a precision threaded plastic barrel. The lens assemblies (Sunex Inc. Carlsbad, CA, USA), are F/#3 with a 5.9 mm focal length. The position of each lens is individually adjustable by simply rotating the lens assembly with respect to the lens plate, allowing each lens to be independently focused.

Interposed between the lens plate and the CCD chip is a foam light baffle which prevents crosstalk between sub-images. The light baffle is laser-cut from 1/8" (3mm) thick, closed cell, black foam rubber, with 7mm holes matching the positions of the lens assemblies. The foam rubber is sufficiently thick as to be slightly compressed by the lens plate, and is soft enough that direct contact with the front surface of the CCD neither displaces nor damages the CCD. The diversity plate is placed in front of the lens plate. The diversity plate is designed to accommodate up to 18 separate optical elements, each approximately 5mm in diameter (or approximately 5mm square). The diversity plate shown in figure 2 is composed of a variety of spectral filters, polarizers, neutral density filters and a cubic phase element used for extended depth of field. Other diversity plates have been fabricated and tested as shown later in this paper.

3. APPLICATIONS OF THE PERIODIC CONCEPT

In the next few sections we will highlight several specific applications of the PERIODIC concept. Each application follows the same general process, depicted in Figure 3, of image acquisition, subimage segmentation and registration and the final step of image reconstruction.

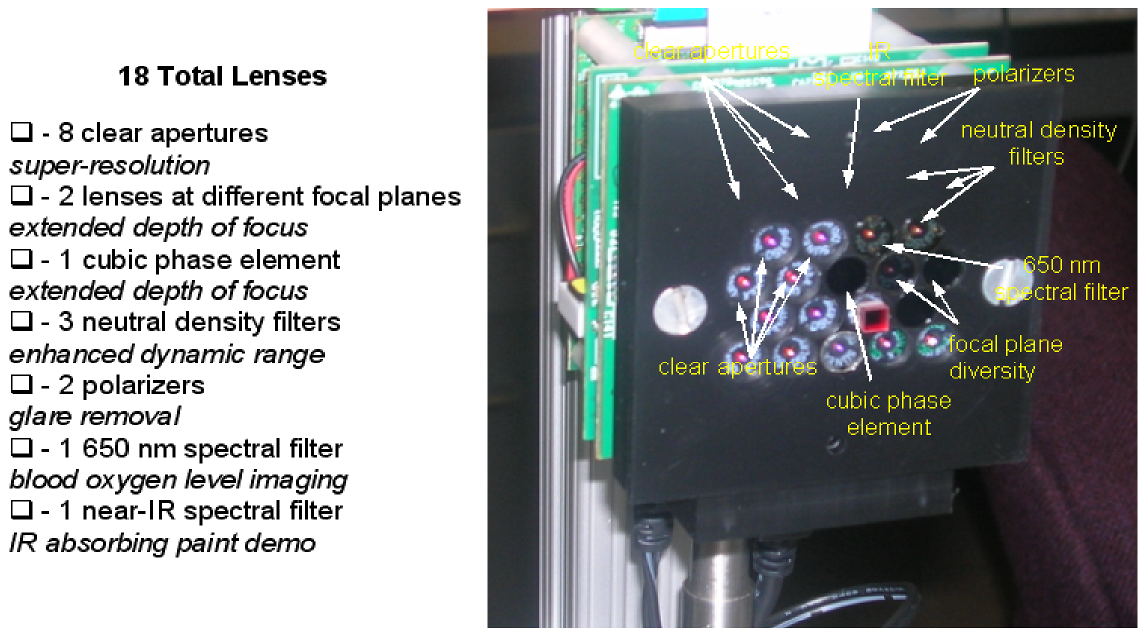

Figure 2. A PERIODIC prototype camera consisting of a large 10.6 Mpixel CCD, 18 small cell phone lenses and a diversity plate containing a variety of optical elements.

<u>3.1 Application of PERIODIC to digital super resolution</u>

Computational methods for resolution improvement have attracted much attention lately due to their ability to enhance the performance of inexpensive, lower resolution sensors. See, for instance [1-4]. Superresolution (SR) is based on a simple idea: the different information encoded in a series of low-resolution (LR) images is used to recover one high-resolution (HR) image. This concept works well when resolution is limited by the size of the imaging pixel and not the optical diffraction limit. A multi-aperture approach to digital super resolution was recently explored by the TOMBO group [1,2].

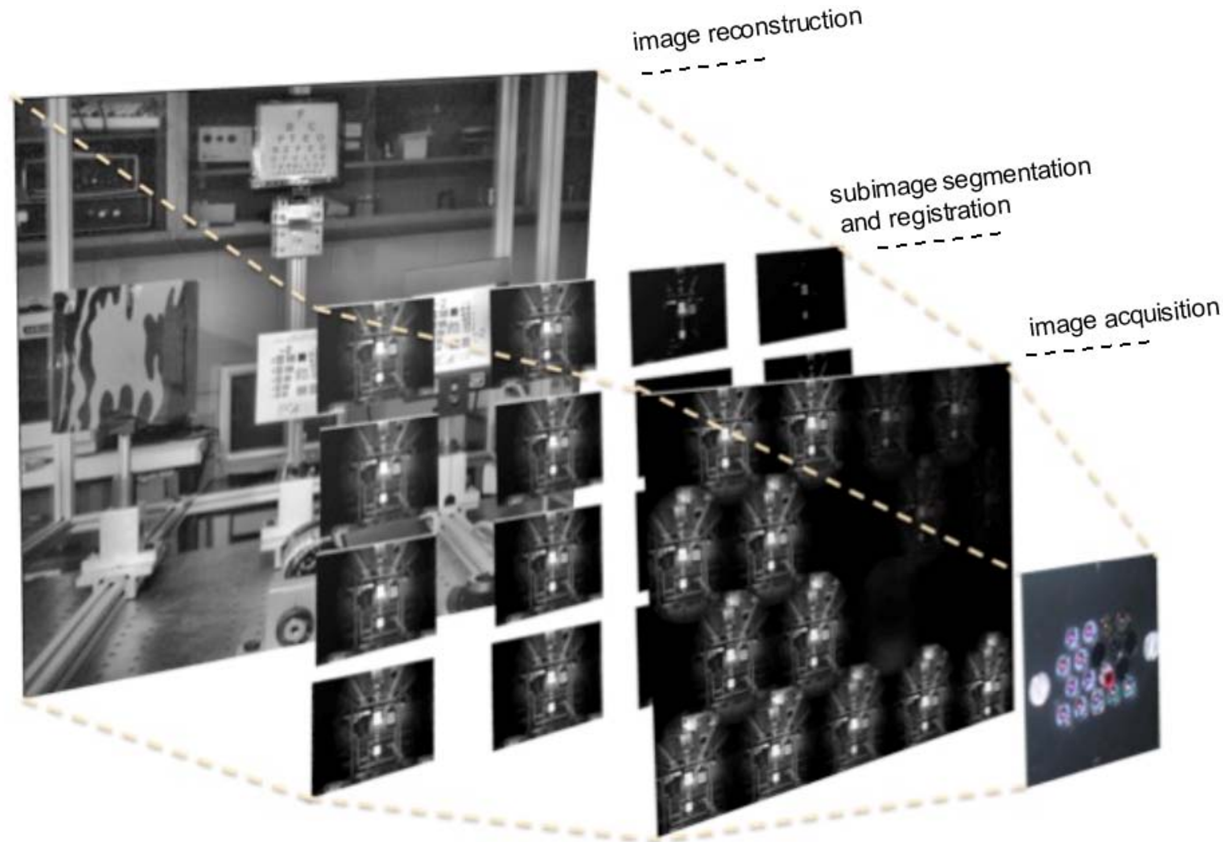

Figure 3. General process used for PERIODIC applications of acquisition of multi-aperture raw image, subimage segmentation and registration and the final step of image reconstruction.

The basic digital super resolution problem can be posed as an inverse problem

$$\min_{f} \| DH_i S_i f - g_i \|_2^2, \quad i = 1, \ldots, l^2 \qquad (1)$$

where f is the vectorized true high resolution (HR) image, g_i is a vectorized lower resolution (LR) image, D is the decimation matrix, H_i is the blurring matrix, S_i is a shift matrix and l is the upsampling factor. The decimation matrix D is a local averaging matrix that aggregates values of non-intersecting small neighborhoods of HR pixels to get LR pixel values. The shift matrix S_i, also called the interpolation matrix, assigns weights according a bilinear interpolation of HR pixel values to perform a translation of the original image. The blurring matrix H_i is generated from a point spread function (PSF) and represents distortion from atmospheric and other sources. Usually, the l^2 matrices $DH_i S_i$ are stacked to create one large problem

$$\min_{f} \| Af - g_i \|_2^2 \qquad (2)$$

where $A = [DH_i S_i ; \ldots ; DH_i^2 S_i^2]$ and $g = [g_1 ; \ldots ; g_l^2]$. Here $A \in \Re^{n^2 \times n^2}$.

The basic process for digital super resolution involved the following steps: (1) capture a number of low resolution subimages using the PERIODIC camera, (2) perform image segmentation and registration on those images (note: that registration must be conducted on a subpixel level) and (3) solve the inverse problem describe above to determine the high resolution reconstructed image. The theoretical gain in resolution using this approach will vary as the square root of the number of subimages (N). The practical limit due to noise, errors in registration and other artifacts will likely be somewhat less than this value.

Figure 4. Digital super resolution reconstruction (shown on the left) of low resolution multi-aperture images captured with the PERIODIC camera. For this example 16 low-resolution subimages were used for the reconstruction. The measured resolution improvement was approximately 3X.

3.2. Application of PERIODIC to multi-spectral imaging

Hyper-spectral or multi-spectral imaging techniques provide the means to extract additional information from the scene in a wide variety of applications, ranging from remote sensing [5,6] to biomedical imaging [7,8] to target recognition and tracking [9,10]. Hyper-spectral imaging suffers from a significant drawback in that the traditional approach to hyper-spectral imaging is not well suited for imaging motion. Traditional hyper-spectral imaging systems, which rely on either “push-broom” or tunable bandpass methods, require increased acquisition time to scan either the scene or the spectrum. This increased acquisition time compromises the performance of such systems when imaging dynamic phenomenon or moving objects. When composite images are formed by combining data from different parts of the spectrum, any significant motion in the scene creates motion artifact which appears as edge enhancement or feature distortion in the composite image. Additionally, while hyper-spectral imaging provides the possibility of acquiring all the spectral information in a scene, it is a technique that requires the acquisition and storage of vast amounts of digital data. It is, therefore, computationally intensive to sift through the complete hyper-spectral cube to find the desired information. In many cases, the acquisition of the complete hyper-spectral cube provides little additional information as compared to multi-spectral imaging, wherein images are acquired only in a series of discrete spectral bands. Given the fact that most materials in nature do not show sharp or narrow-band spectral characteristics, a set of appropriately chosen bandpass filters provides sufficient spectral resolution to quantify a wide variety of physical phenomena.

For particular imaging applications, some *a priori* knowledge of a spectral signature can allow the rapid extraction of useful information from a significantly smaller data set, obtained by imaging in several discrete spectral bands. Algorithms for pixel-wise data clustering and target recognition have been developed for cases where no *a priori* knowledge of the spectral characteristics exists. Additional useful information may be obtained by imaging with other optical elements such as polarizers, neutral density filters, or phase masks. These optical elements provide a range of "optical diversities" with which a scene may be interrogated. Multi-spectral imaging using bandpass filters provides additional benefits in terms of cost and size or form factor. The cost of narrow band interference filters is generally much lower than the cost of tunable filters. Interference filters do not require the electronics and RF power supplies commonly used with acousto-optic tunable filters (AOTF). This technique is therefore well suited for the fabrication of small, light weight, "fieldable" systems.

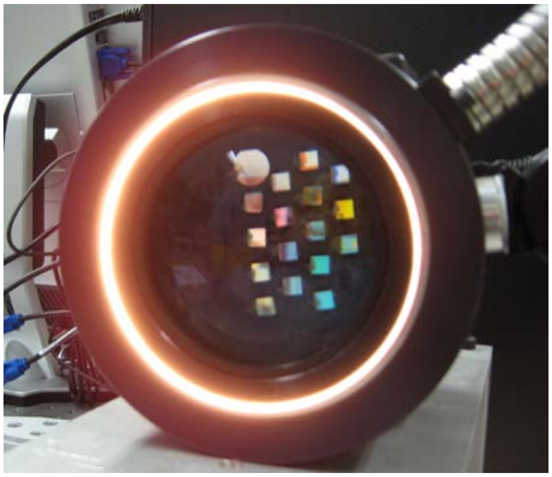

Figure 5. Multi-spectral PERIODIC prototype.

Given the considerations discussed above, combined with the notion that pixels are rapidly becoming less and less expensive, we propose a multi-spectral imaging system that acquires multiple images simultaneously, through multiple, independent imaging channels. This approach constitutes an effective, low cost system for many multi-spectral imaging applications, especially those where motion artifact is an issue. This strategy takes maximum advantage of the increase in sensor resolution and the decreased cost-per-pixel associated with the digital photography revolution. To this end, we have designed and constructed a multi-spectral PERIODIC camera using 18 individual lenses and narrow bandpass filters, forming 17 separate wavelength dependant sub-images on a single CCD frame (shown in figure 5).

Each frame acquired from the CCD requires additional post-processing. A registration algorithm and software interface have been developed which process the images such that the user is required to enter only minimal data. The software acquires a frame from the CCD, parses and crops the complete image into 18 separate sub-images, and then registers the sub-images. The various sub-images are then mathematically combined according to any recipe or weighting function the user specifies.

Figure 6a shows a conventional photograph of a MacBeth® color-checker chart acquired with a conventional digital camera. Figures 6b and 6c show composite images created by combining various sub-images of the PERIODIC camera i such a way as to enhance specific spectral characteristics. Figure 6b is generated by adding three sub-images, with wavelengths in the red, and subtracting three sub-images in the yellow, green and blue. As a result, tiles reflecting red are enhanced, while all other tiles are suppressed. Figure 6c,

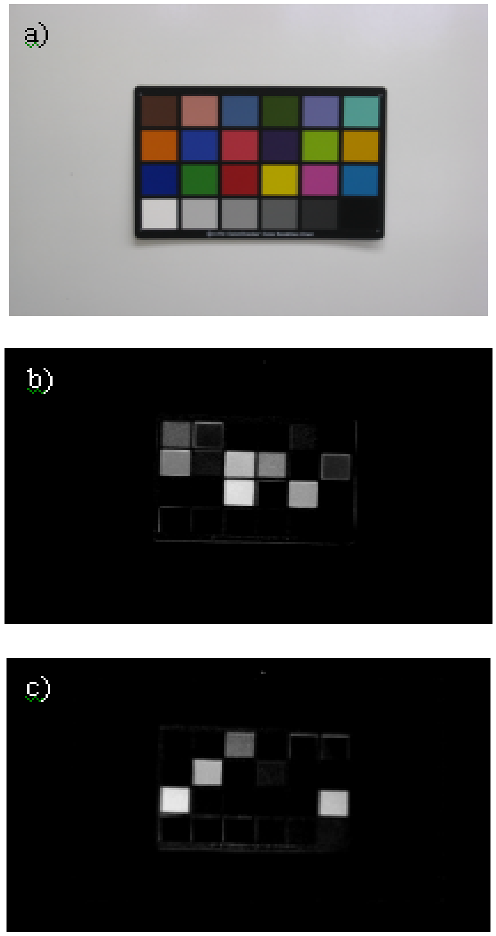

Figure 6. a) A Macbeth® color chart photographed with a conventional camera [color online]. b) A composite image showing red enhancement. c) A composite image showing blue enhancement.

created from the same multi-spectral image, demonstrates a similar enhancement of blue tiles.

While a similar demonstration could be done using a conventional digital camera, by manipulating the red, green, and blue pixel values, any quantitative spectral measurement or spectral un-mixing technique would be far less precise given that RGB or Bayer type filters provide only three spectral data points, each integrated over a fairly wide band of wavelengths. By using 17 narrow band spectra, this system is capable of gathering data with significantly more spectral information.

3.3 Application of PERIODIC to enhanced dynamic range imaging

Many amateur and professional photographers can easily appreciate the problems associated with trying to image high dynamic range scenes. Adjusting camera settings in an attempt to capture details within the dark areas or shadowed areas while not saturating the bright areas can be very difficult. Attempts to design high dynamic range cameras have concentrated on two main methods. The first utilizes custom imaging sensors specifically designed for high dynamic range applications [11]. This method is an attractive solution but may not currently be cost effective for many potential users. A second technique, less expensive method, combines a sequence of images taken at various exposure levels [12]. These images are then computationally combined to create a composite high dynamic range image. This method works well for static images but not for moving targets. In our approach we also acquire several images at variable "effective" exposure levels. However, we employ a series of neutral density filters to create the various exposures. These subimages are then computational combined to reconstruct a composite high dynamic range image. The advantage of our approach, over the sequential technique, is that we acquire all the subimages in a single camera exposure time. Thus we could theoretically apply this method to moving objects.

The image formation problem for high dynamic range reconstruction is also posed as an inverse problem given by

$$Z_{ij}^{n} = f(E_{ij} \cdot 10^{-D_n}) \tag{3}$$

where $Z_{i,j}^{n}$ is the pixel count at location (i,j) of subimage n, D_n is the optical density of the n^{th} neutral density filter, f is the camera response function and E_{ij} the irradiance at pixel (i, j). The goal is to estimate the true pixel irradiance, E_{ij}, given the other parameters. We employed a conjugate gradient (CG) based iterative algorithm to solve the inverse problem posed in (3).

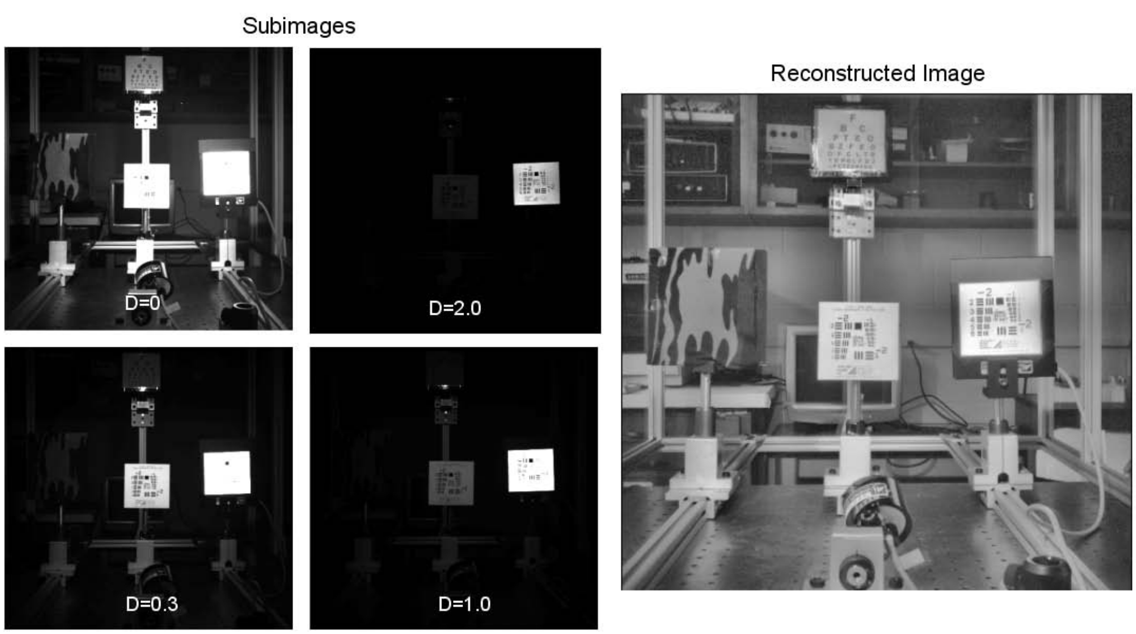

Figure 7. High dynamic range reconstruction based on four subimages each with different optical density filters.

In Figure 7 we show the results for a test image generated in the laboratory. Here we purposely constructed a high dynamic range scene with very bright sources and dark regions. We used four imaging channels each of different neutral density filters with optical densities ranging from 0 to 2.0. The method described above was then used to reconstruct a single high dynamic range image from those four subimages.

4. SUMMARY AND CURRENT WORK

We have presented a novel integrated computational imaging platform capable of capturing and exploiting information-rich data in near real-time. Applications including digital super resolution, multi-spectral imaging and enhanced dynamic range were presented. In addition to these results we are currently exploring several additional applications including exploiting spectral-polarization information for image dehazing and digital super resolution combined with 3D imaging.

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