PERIODIC: Integrated Computational Array Imaging Technology

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Abstract: An integrated array imaging system, dubbed PERIODIC, is presented which is capable of exploiting diversities including sub-pixel displacement, phase, polarization, neutral density, and wavelength, to produce high definition images. The optical hardware system and software interface are described, and sample results are shown.

OCIS codes: (130.3120) Integrated optics devices, (110.4190) Multiple imaging

1. Background:

Array imaging is an emerging paradigm where a specially designed array of lenslets is employed to capture an ensemble of images of a subject, enabling the collection of significantly more information than possible with conventional single-lens imaging systems. Thin form-factor and wide field of view are often important additional characteristics of an array imaging approach.

In this paper, we present an integrated optical-digital array imaging system, dubbed PERIODIC, capable of exploiting sub-pixel displacement, phase, polarization, dynamic range by neutral density filters, and wavelength diversity to produce high definition or multi-layered images of different targets. The optical hardware and software interface of a PERIODIC camera prototype are described. The optical sensor and software components work in concert to solve underlying complex image registration and reconstruction problems in near real-time. We also show and explain sample applications of the prototype camera.

The main thrust of integrated imaging systems has slowly but surely begun to shift toward systems that can maximize information content of images relative to a set of prescribed imaging tasks. While digital processing is an essential ingredient of this approach, it is distinguished from conventional systems in its being tightly coupled with the optical component of the system.

Array imaging systems are an important step in the design of optical-digital integrated imaging systems capable of outperforming single-lens systems while maintaining a thin form-factor and wide angle of view. Recently, a number of research efforts have investigated the potential of lenslet array camera systems, notably the TOMBO [1, 2] project and the MONTAGE [3] projects. The PERIODIC camera concept, created under a seedling Disruptive Technology Office (DTO) challenge grant, seeks to explore and exploit a broad variety of observational diversities which can be inherent in lenslet array-based systems, including phase, polarization, dynamic range, and wavelength diversities.

A significant milestone in our investigation is the development of a PERIODIC camera prototype able to greatly improve the resolution and dynamic range of imagery, remove glare, and perform spectral filtering in near real-time. These tasks require integrated optical sensor and digital components working in tandem to solve complex ill-posed image registration and reconstruction problems. As such, it is representative of the state-of-the-art in the field of array imaging.

2. Hardware and Software Integration

A three-pronged approach consisting of information theoretical, optical design, and computational studies was taken to explore the theoretical and practical limitations [4], performance trade-offs, and applications [5] of multi-diversity lenslet array-based systems. An integrated optical-digital PERIODIC camera prototype was developed as a result of these investigations.

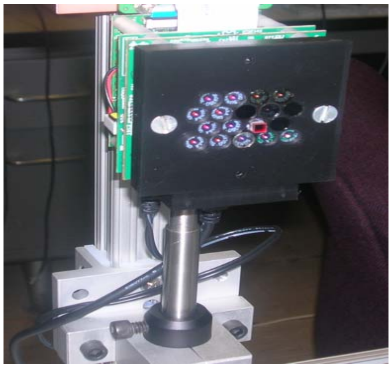

Figure 1 shows a picture of the optical hardware component. This camera was built upon a large format 10 MPixel CCD detector array supplied by Lumenera Inc. A lenslet array consisting of 18 small (2.0 milimeter aperture, 5.0 mm focal length) cell phone lenses (supplied by Sunex Inc.) was mounted over the surface of the CCD array. A second mounting plate containing a variety of different optical elements was aligned and mounted over the lenslet array. The different optical diversities consisted of eight clear apertures (i.e. no diversity), three neutral density filters, two polarizers, a cubic phase diffractive optical element and two spectral filters (650 nm and near-IR). This combination of diversities was able to capture an information-rich raw image over a single ten megabit detector plane.

Figure 1: PERIODIC prototype: optical array imaging components.

The digital component consists of a graphical user interface front-end and a computational back-end. The front-end follows a flexible object-oriented design that is self-reconfigurable with respect to the camera lenslet and detector specifications. The back-end consists of a set of numerical methods for efficiently solving sub-image registration, reconstruction, and deconvolution problems in near real-time.

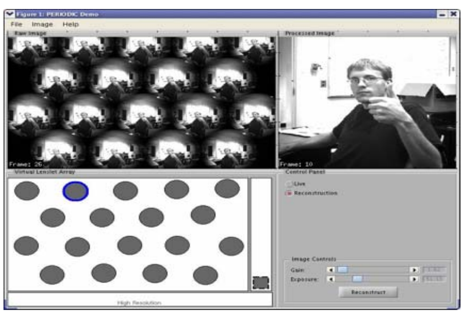

Figure 2 shows a screen shot of the camera prototype front-end computational setup. Two major modes of operation are implemented: live and reconstruction. In live mode, video data from individual lenslets can be selected and processed by the user in real time. In reconstruction mode, the user can apply high resolution, high dynamic range, or phase-encoding reconstruction to selected lenslets. Pixel and sub-pixel level registration is performed if needed for the reconstruction. An IBM Thinkpad T60 laptop running Linux was used for the computational tasks and for the camera interface.

Figure 2: PERIODIC prototype: digital component front-end.

3. Sample Test Results

The PERIODIC camera prototype was tested under a variety of conditions and imaging tasks. Figure 3 shows the result of digital superresolution (right) from a set of eight low resolution images. A typical low resolution image is shown on the left. Additional applications to iris recognition biometrics for personnel identification and verification are provided in by the authors in [5].

Figure 3: Superresolution reconstruction by PERIODIC lenslet array camera.

Figure 4 shows glare removal (on the right), and Figure 5 shows identification of wavelength encoded information (faint USA letters in image on the right) obtained through near-IR spectral filtering. Results on dynamic range reconstruction and depth-of-focus extension are omitted due to space constraints.

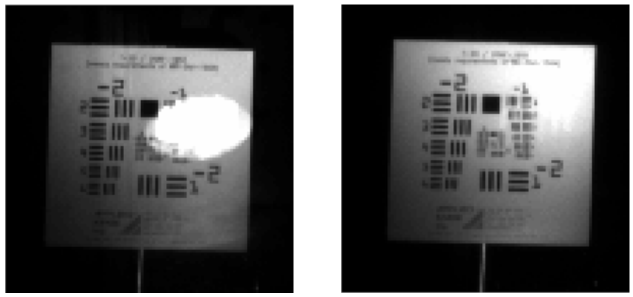

Figure 4: Conventional image versus polarized for glare removal by PERIODIC lenslet array camera.

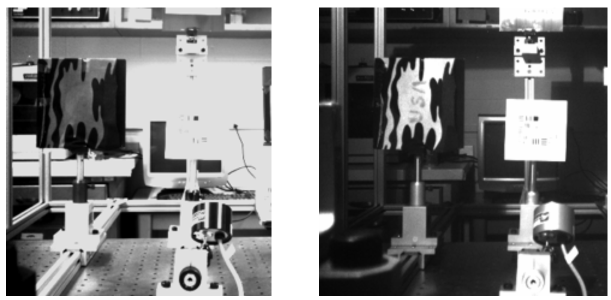

Figure 5: Conventional image versus spectral for target identification by PERIODIC lenslet array camera.

4. Summary and Current Work

We have presented a novel integrated optical-digital lenslet array imaging system, capable of capturing and exploiting information-rich data in near real-time. Apart from the results demonstrated above, we have been able to apply the concept of Fisher information to obtain useful theoretical upper bounds on the fidelity of reconstruction of high-resolution images from low-resolution image sequences. The prototype PERIODIC camera system has shed much light into the design and versatility of lenslet array systems. Still, the full space of design parameters remains largely unexplored. Many aspects need and will be considered in the future. These include the use of diffractives; GPU integration; and joint approaches for registration and reconstruction, a difficult nonlinear numerical optimization problem.

5. References:

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