Field Test of PANOPTES-Based Adaptive Computational Imaging System Prototype

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Abstract: We describe the design and prototype development of a visible-band, multi-resolution, steerable computational imager in a flat profile, based on the PANOPTES architecture. We present this imager’s superresolution capabilities via field test results.

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1. Introduction

This paper presents the results of our efforts towards realizing a working prototype of a multi-aperture, adaptive, flat, computational imaging sensor based on the PANOPTES (Processing Arrays of Nyquist-limited Observations to Produce a Thin Electro-optic Sensor) concept. In previous work, we presented the PANOPTES concept which consists of multiple sub-imagers, each with its own steering mechanism [1-3]. The PANOPTES architecture allows for adaptive imaging in a multi-aperture, flat-profile configuration. This adaptability is realized through steering mirrors to maneuver each sub-imager’s field of view (FOV), thereby enabling dynamic, non-uniform spatial allocation of imaging resources to match the information content of the scene [4]. The goal of this prototype development effort was to demonstrate digital super-resolution (DSR) capabilities in the visible band via precision steering capability within a multi-aperture, folded optical, flat form factor imaging configuration. The optical design and hardware development of this prototype was undertaken at The Charles Stark Draper Laboratory (Draper), while the control software was developed at Southern Methodist University (SMU). This imaging system was then field-tested at the White Sands Missile Test Range (WSMR) in White Sands, NM.

2. PANOPTES Prototype Breadboard Overview

The PANOPTES prototype comprises of five individually addressable optical channels, with one wide field-of-view (WFOV) center imager providing situational awareness and four narrow field-of-view (NFOV) steerable (i.e., roaming) imagers providing the requisite conditions for accomplishing DSR. The fields of view for the roaming imagers are capable of being individually or jointly steered to regions of interest within the FOV of the center imager. The optical blur size of the steerable NFOV imagers is roughly one-half the pixel pitch of these imagers, thereby allowing for up to a factor-of-four resolution enhancement (based on Rayleigh limit calculations). The pixel arrays in the steerable imagers consist of square pixels with unity fill-factor (i.e., pixel pitch equals pixel size). Figure 1(a) illustrates the conceptual design layout of the PANOPTES prototype, while Figure 1(b) shows a frontal photograph of the PANOPTES prototype, as built and tested. DSR is accomplished by capturing a set of images with the roaming imagers such that each image within a given set would be a sub-pixel shifted version of the image with respect to all other images within that set. The magnitude of this sub-pixel shift is then a driving factor in determining the resolution gain obtainable from the DSR algorithm.

Steering of each roaming imager is accomplished using two mirrors for azimuth and elevation control, and piezo actuators to shift its CCD detector. A key requirement of this PANOPTES prototype calls for high-precision steering capability for the roaming imagers to enable sub-pixel shifts of one-tenth of a pixel, thus eliminating positional accuracy as a limiting factor in realizing DSR. This level of pointing precision via steering is realized through a two-step process which involves (1) coarse-precision steering using rotational motors and (2) fine-precision steering with dual-axis nano-positioning piezo actuator stages. The former yields pointing accuracy to within one-fifth of a pixel while the latter enables further precision on the order of a few hundredths of a pixel.
The piezo stages further allow the flexibility to dither the roaming imagers such that sub-pixel shifting may be achieved either (a) spatially through FOV overlap of each of the roaming imagers by designated sub-pixel shifts or (b) temporally through dithering the piezo stages on each imager by a specified transverse distance. While spatial sub-pixel positioning would require the coordinated efforts of all four NFOV imagers (thereby limiting the resolution gain to a factor of two along the horizontal and vertical direction), temporal dithering may be accomplished by each individual steerable imager on a standalone basis. Resolution gain from the second method can therefore in principle approach the limit of DSR gain dictated by the optics and the pixel size of the imager. Furthermore, the latter approach would not need to compensate for the relative image rotations between the four roaming imagers due to the spatial diversity arising from the physical layout of these roaming imagers.

3. Prototype Field Testing

Following system integration, the PANOPTES prototype was tested, both in laboratory conditions and in field test conditions at WSMR. Laboratory testing consisted of stepper motor and piezo characterization, as well as NFOV imager calibration and testing using a collimated point source and an autocollimator. Field testing was conducted in February 2011 at the Army Research Laboratory Electro-Optical Vulnerability Assessment Facility (EOVAF) at White Sands Missile Range. The field-test scenarios involved setting up the PANOPTES prototype on a vibration-isolated optical table in the EOVAF DUT-building and observing stationary targets at distances of 300, 800, and 1800 meters downrange, in both nighttime and daytime environments. Several targets were used jointly as well as separately as representative scenarios in the test setup. These targets consisted of a Humvee, a back-illuminated resolution target and a truck – all of which were graciously provided by the EOVAF facility.

4. Digital Super-Resolution Results

The images captured during the WSMR field test (described in the previous subsection) were then subjected to DSR reconstruction to obtain high-resolution imagery. The DSR method used is known as super-resolution with unsharp masking (SRUM), which we first introduced in [5]. This method involves embedding an unsharpening mask into the fidelity term of a well-defined cost function, which results in reconstructed images with better visual perception. The unsharpening mask has the effect of highlighting edges and details. Figure 2 shows some of the DSR results obtained on the bar target images while Figure 3 shows resolution enhancement in the Humvee image. Each image set was captured at night, with sub-pixel shifts of one-quarter pixel along both the horizontal and vertical directions. As seen from Figure 2 and Figure 3, the increase in resolution is evident from the reconstructed results. In all these cases, the reconstructed images are a factor of four larger than the original image in both horizontal and vertical directions, given that the image sets consisted of quarter-pixel-shifted low-resolution images.
Figure 2: Results of SRUM algorithm applied to a number of nighttime images of bar targets (WSMR data). Top row: Original low-resolution images. Bottom row: Reconstructed HR images. The target ranges are 300 meters, 800 meters and 1800 meters for the left, center and right columns of images respectively. Spatial frequencies of the resolution targets were as follows: (a) left column: 0.67, 1.34, 2.7 and 6.74 times Nyquist; (b) center column: 1.8× Nyquist; and (c) right column: 4× Nyquist. Resolution enhancement up to 4× Nyquist was realized through DSR with this imager and is clearly evident at all ranges at which the imager was tested.

Figure 3: Results of SRUM algorithm applied to nighttime images of the Humvee (WSMR data). While resolution enhancement is evident throughout the image, a notable highlight is that one may easily count the number of wheel nuts on the final high resolution image – a feature indistinguishable in the captured low resolution image.

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6. References