PANOPTES: A thin agile multi-resolution imaging sensor.

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Abstract: A thin, agile, multi-resolution, computational imaging sensor architecture, termed ***PANOPTES***, that utilizes arrays of MEMS micro-mirrors to adaptively redirect the fields-of-view of multiple low-resolution sub-imagers, is introduced. An information theory-based super-resolution algorithm restores the image..

Keywords: Computational Imager, Flat Imager, MEMS.

Background / Motivation

The desire for information superiority in matters of national security has created a requirement for pervasive optical sensors with flat form factors. Traditional imaging systems contain a lens, and the quality of the resulting image is typically proportional to the physical size of the lens used. Both the light gathering capability and the resolving power of the imaging sensor derive directly from the size of the optical elements in such systems. This fact ultimately results in imaging devices that are bulky and cube-like – a constraint that has persisted since their invention. The costs associated with the design, manufacture, and packaging of such physically unwieldy systems have made them a relatively scarce resource in many scenarios where their pervasive use would be beneficial.

One only needs to consider recent developments in flat panel technologies to gauge the possibilities for a flat imaging sensor. Flat displays are easier to place, take up less physical space, and are ultimately more useful because of their form factor.

The creation of a flat imaging sensor requires a paradigm shift in imaging system approach coupled with a proper selection and integration of emerging technologies [1]. Traditional imaging sensors utilize a lens or mirror to form the image that is then sampled onto a detector array. A thin optical sensor would be restricted to using smaller optical elements and therefore require additional computation to complete the image formation. Flat imaging sensors based on arrays of micro-optical elements have been proposed and prototyped [2]. These sensors place many imaging resources on each region to be imaged to provide the necessary data for additional computation to enhance the inherent resolution of the flat sensor. One constraint of the approach in [2] is the fixed overlap of the imaging resources, requiring the design to be optimized for a specific resolution and field-of-view. Clearly, adaptive sensor elements would increase the utility of flat cameras.

Technologies developed in the late 1990's offer an opportunity to create a useful and flat micro-optical imaging sensor. Micro-mirror arrays, similar to the ones used in many laptop projectors today, have been demonstrated in novel imaging and signal processing systems [3]. The precision and optical quality of these micro-mirror arrays make them attractive candidates for a flat micro-optical imaging sensor. The use of analog steerable micro-mirror arrays makes it possible to direct imaging resources at will [4]. Envision a flat optical sensor that contains a multitude of low resolution micro-optical sensors, each of which is being steered using precision micro-mirror arrays towards regions-of-interest—an *attentive multi-resolution imager*. Multiple low-resolution sensors interrogate these regions-of-interest, and the resulting data is digitally processed to extract high-resolution detail from the data. Regions with no features of interest are imaged with relatively low resolution, and areas of interest are continually updated with increasing resolution – up to the optical resolution limit. Such a system can approach the performance of a high-resolution bulk imaging device – and even potentially surpass it in situations where only a small portion of the image field is of interest.

There are numerous possible applications for such flat imaging devices. A UAV could be tiled with flat imaging sensors that survey the entire scene simultaneously. A soldier's helmet could contain many lightweight flat imaging sensors which report data not only to the soldier but to command operations as well, all without adding physical weight or hindering the user's movements. Physical security assets could have hallways tiled with attentive flat sensors for which no one can determine if they are being observed. Form factor is the single greatest obstacle to prevalent image gathering today, and the necessary technologies have emerged to fundamentally change the way we collect images.

Computational Sub-sampling Approach

In order to clarify the use of computational imaging for sub-pixel resolution as used in [2] and used adaptively in the ***PANOPTES*** architecture, let us use a typical digital SLR as a candidate design for reducing the form factor by a factor of 10, and look at the ramifications. The baseline camera has a focal length of 5 cm, lens aperture of 2.5 cm and a detector pixel size of 10 μm. It follows that the instantaneous field-of-view (IFOV) of a single detector is 10 μm/5 cm = 0.2 mrad. If we aim to reduce the working distance of this baseline system by an order of magnitude we can consider using instead a lens of focal length 5 mm and aperture 2.5 mm. However, we are unable to reduce the size of the pixels in the detector commensurately (to 1 μm) due to both manufacturing constraints and light collection (SNR) constraints. If we keep our 10 μm detector pixel size, then the new IFOV is 10 μm/5 mm = 2.0 mrad. We have lost an order of magnitude in angular resolution of the sensor. Yet the diffraction limited spot size remains the same as the f# of the lenses are equal. In fact, the diffraction limited spot size of the system remains ~5 times smaller than our detector size. Herein lies the benefit of the computational sub-pixel processing approach. By replicating the miniaturized optical system many times with precise offsets that are less than individual detector IFOVs, super-resolution signal processing techniques can be applied to reconstruct up to the diffraction limit of the optical systems [5]. Now instead of each detector having a non-overlapping IFOV of 0.2 mrad for a total field of view of 200 mrad (with a 1000x1000 detector array) we have an array of 10x10 sub-imagers (SI) each with 100x100 pixels and a corresponding field of view of 200mrad, but interleaved to sample the object space to allow a reconstruction algorithm to restore the image to 0.2 mrad resolution. It should be noted that we are not proposing to perform super-resolution in an optical sense (near field effects), only in a signal processing sense to achieve the fundamental optically limited resolution. In the PANOPTES archticture adaptive sub-pixel overlapping IFOVs will be created through the use of 2-D analog micro-mirror arrays.

Discussion

We introduce a novel flat image sensor concept termed ***PANOPTES*** (***P***rocessing ***A***rrays of ***N***yquist-limited ***O***bservations to ***P***roduce a ***T***hin ***E***lectro-optic ***S***ensor). It derives its name from *Argos Panoptes* – a mythological giant with 100 eyes who was all seeing (panoptes), and was thought to be the ultimate sentry. Like this mythical character, the ***PANOPTES*** architecture seeks to extract all the relevant information from a scene, yet is capable of adapting to any scenario. This objective can be achieved with an order-of-magnitude decrease in sensor thickness relative to a conventional camera with similar performance. The proposed architecture can be likened to an adaptable steerable field-of-view version of TOMBO [2]. Adaptability is paramount to the success of an imaging sensor attempting to meet this flat form factor goal and high image quality.

Based on the information theory of imaging described in [6,7], the spatial information available within a scene is typically non-uniformly distributed. Take, for example, Fig. 1, an aerial view of airplanes parked at an airport terminal. Fig. 2 is a mapping of local entropy at lower resolution, corresponding to the local information content of the image in Fig. 1. From Fig. 2, it is clear that there is a strong correlation between our subjective view of information-rich regions of the image and the spatial entropy, which can be exploited in designing an adaptive imaging sensor. It is also evident from Fig. 2 that uniformly applying the limited imaging resources, as in a traditional camera, is wasteful. What is needed is a strategy that optimizes the information efficiency (the number of bits of information per bit of data the sensor system outputs for a given scene) of the sensing device. The ***PANOPTES*** architecture adaptively applies imaging resources to match the information content of the scene and approaches the performance of a traditional imaging sensor while reducing the thickness of the sensor by an order-of-magnitude.

This architecture achieves the required adaptability using micro-mirror technology originally developed for photonic switching. Fig. 3 is a schematic depiction of the concept. It is a tiled architecture, where each tile consists of a small array of detectors, an optical quality 2-D analog micro-mirror array, and a transparent superstrate containing the required micro-optical elements. The scene is imaged onto

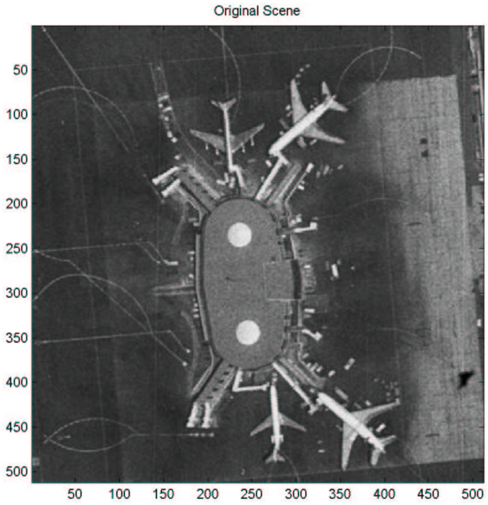

Fig. 1. Aerial image of an airport terminal.

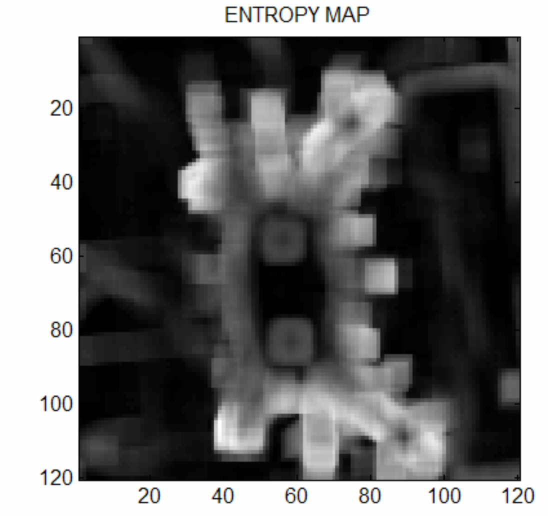

Fig. 2. Information content map to identify regions of interest for the sample airport image in Fig. 1.

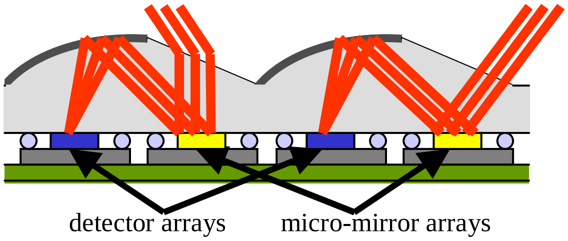

Fig. 3: ***PANOPTES*** tiled approach.

the relatively low-resolution detector array by a folded optical system that has the micro-mirror array at its pupil. Such configurations have been pursued in parallel with this effort by others [8] for steering single aperture, non-computational, bulky imaging systems. Locating the micro-mirror array at the pupil of the imaging system allows it to steer the field-of-view of the detector array.

Fig 4: Photo of Washington, DC.

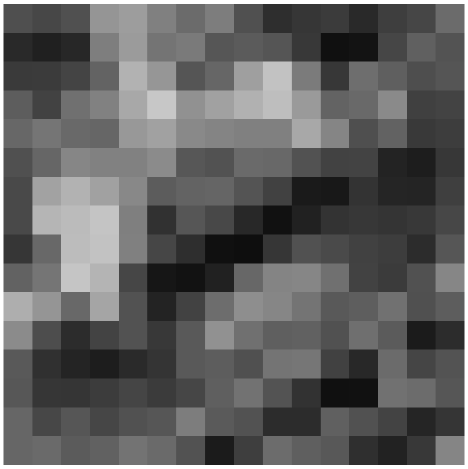

Fig. 5: Output of a single SI.

This adaptability permits each individual detector array to have a narrower field-of-view and therefore improves the angular resolution of individual detector elements. Improved physical angular resolution relaxes the demands put on the reconstruction algorithms.

Information theory-based metrics drive ***PANOPTES*** to re-orient micro-mirror arrays to enhance the information rate obtainable from the visual scene over several signal frames using a feedback mechanism. This enables new adaptive algorithms, ones in which the actual sensor adapts to acquire the desired data, instead of those that merely post-process the data according to the signal statistics. Additionally, the ability to create precise absolute geometric changes in sensor content via micro-mirror positioning allows a signal structure to be built that admits a simple, local computational structure that can easily be distributed across multiple digital processors.

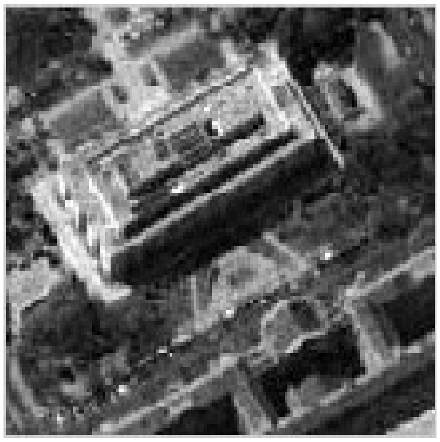

Fig. 6: Image reconstruction from Fig. 5.

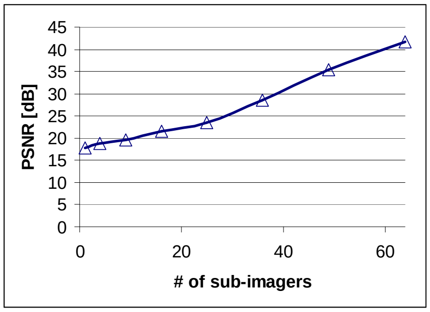

Fig. 7: PSNR of reconstruction vs. SI number.

A preliminary reconstruction algorithm was developed as part of the conception and initial validation of the ***PANOPTES*** concept. This algorithm fuses information from multiple sensors that collect over-lapped, but slightly shifted (by amounts corresponding partial pixels in the raw low-resolution imagery), low-resolution images. Fig. 4 shows an example input scene and Fig. 5 is an example low-resolution imagery that would be obtained from a sub-imager. The image patch at which the sub-imagers (SIs) are pointed is indicated by the square in Fig. 4 and the output of one of these SIs without any overlap is given in the inset. The output of each SI is highly pixilated and does not contain sufficient information about the object. As shown in Fig. 6, we reconstructed the image from a collection of many such pixilated looks using a simple Wiener filter. The PSNR of the reconstructed image with increasing number of blurred observations of the object is given in Fig. 7. As expected, the quality of the reconstructed image increases with an increasing number of overlapped SIs. The quality of the reconstructed image was as high as 41 dB. Operating points of the system can be chosen based on performance curves that measure information content. The minimum number of SIs required to apply to a particular part of the image to obtain the desired quality and information can be determined by analyses like that which produced Fig 7. These will result in adaptive algorithms which drive SI resource allocation.

Conclusion

A key feature of the ***PANOPTES*** concept is its capability – using precisely controllable MEMs-mirror arrays in the sensor pupil plane to vary the position of the FOV of sub-imagers – to adjust the quality of the reconstructed image depending on it’s information content. To achieve this capability, novel adaptive algorithms are being developed to manage and adjust sensor positioning. These strategies will be truly adaptive in that measurements of the quality and resolution of the reconstructed image portions will be used to change the look directions of the optical sensors over a sequence of images. As described, the ***PANOPTES*** architecture is an adaptive multi-resolution attentive computational imaging sensor architecture that directs its resources based on the information content and distribution across the scene.

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