LETTER

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Multiscale gigapixel photography

D. J. Brady[1], M. E. Gehm[2], R. A. Stack[3], D. L. Marks[1], D. S. Kittle[1], D. R. Golish[2], E. M. Vera[2] & S. D. Feller[1]

Pixel count is the ratio of the solid angle within a camera's field of view to the solid angle covered by a single detector element. Because the size of the smallest resolvable pixel is proportional to aperture diameter and the maximum field of view is scale independent, the diffraction-limited pixel count is proportional to aperture area. At present, digital cameras operate near the fundamental limit of 1–10 megapixels for millimetre-scale apertures, but few approach the corresponding limits of 1–100 gigapixels for centimetre-scale apertures. Barriers to high-pixel-count imaging include scale-dependent geometric aberrations, the cost and complexity of gigapixel sensor arrays, and the computational and communications challenge of gigapixel image management. Here we describe the AWARE-2 camera, which uses a 16-mm entrance aperture to capture snapshot, one-gigapixel images at three frames per minute. AWARE-2 uses a parallel array of microcameras to reduce the problems of gigapixel imaging to those of megapixel imaging, which are more tractable. In cameras of conventional design, lens speed and field of view decrease as lens scale increases[1], but with the experimental system described here we confirm previous theoretical results[2–6] suggesting that lens speed and field of view can be scale independent in microcamera-based imagers resolving up to 50 gigapixels. Ubiquitous gigapixel cameras may transform the central challenge of photography from the question of where to point the camera to that of how to mine the data.

AWARE-2 is a monocentric, multiscale camera with 120°-by-50° field of view (FOV) and a 38-μrad instantaneous FOV (the angular extent of a single pixel). A monocentric, multiscale camera consists of a spherically symmetric objective lens[3] surrounded by an array of secondary microcameras[2,4,6–9]. AWARE-2 includes 98 microcameras, each with a 14-megapixel sensor. It was constructed as part of the US Defense Advanced Research Projects Agency AWARE programme, which focuses on creating a microcamera platform for scalable, 1–100-gigapixel cameras. Just as the microprocessor is a platform for scalable parallel computing, the microcamera is a platform for scalable parallel cameras with diverse applications in wide-field microscopy, event capture, persistent surveillance and space awareness. As with microprocessors, the designer of microcameras must address granularity and performance trade-offs in selecting aperture and focal plane size, materials and components, and interconnection and processing architecture. Details of the AWARE-2 system design are presented in Supplementary Information, sections 2 and 3. In this Letter, we compare AWARE-2 with previous gigapixel-scale imaging systems, illustrate the capture of a large-scale dynamic event, demonstrate the capacity for high-dynamic-range (HDR) imaging in microcamera systems and analyse the camera's optical resolution.

A gigapixel camera requires a lens system capable of resolving more than 10^9 elements and detectors containing more than 10^9 elements. Designs that address these challenges may be segmented into terrestrial cameras with horizontal 90–120° FOVs (AWARE[4] and Asymmagon; see http://www.gigapxl.org/), airborne surveillance cameras with cylindrical 60–70° FOVs (ARGUS-IS[10] and the multilens array[11]) and astronomical systems with cylindrical 3–4° FOVs (LSST[12] and Pan-STARRS[13]). Design metrics for these systems are provided in Supplementary Table 1.1. Lens design strategies differ between arrays of narrow-field cameras (the multilens array) and single objectives with curved focal planes. Although arbitrarily large pixel counts may be obtained using arrays of conventional cameras, design comparisons confirm, as predicted[1], that the volume of a system with a flat focal plane scales much faster than does that of a design with a curved focal plane. Multiscale design captures the advantage of camera arrays (off-the-shelf focal plane arrays) while avoiding the disadvantage (cost and volume of multiple objective lenses). AWARE uses microcamera arrays to create a large virtual-focal-plane array, in place of precision-mosaicked sensor arrays as used in ARGUS, LSST and Pan-STARRS. The most important points of comparison are that the AWARE design is scalable to larger pixel counts, as illustrated by the AWARE-40 design[4], and that AWARE provides operational advantages over the comparison systems because the focus, gain and exposure of each microcamera can be independently controlled. The disadvantage of the AWARE approach is that a stop must be introduced in the microcamera to balance relative illumination and modulation transfer, thereby increasing system f number (the ratio of lens focal length to effective aperture, which is a measure of lens speed) and volume[4,9]. Bare mosaicked arrays may be preferred for fixed-focus, cost-insensitive airborne and astronomical systems. Multiscale design, however, uniquely makes possible compact, low-cost, terrestrial imaging systems focused at finite range.

The potential for novel science using AWARE-2 is illustrated in Fig. 1, which is a gigapixel snapshot of tundra swans on Pungo Lake in the Pocosin Lakes National Wildlife Refuge, USA. Microcamera data was registered and stitched onto a rectangular grid with 38-μrad instantaneous FOV, to produce a 0.96-gigapixel version of Fig. 1. Non-uniformity correction and logarithmic scaling were applied to improve visual display. Figure 1 is downsampled to 4 megapixels for publication. Raw microcamera images of Fig. 1 regions a, b, c, d and e are shown in Fig. 2. The gigapixel snapshot provides information, such as exactly how many swans are on Pungo Lake (656) or in the air above it (27) at the instant the snapshot was taken, that would be unobtainable using a scanned panoramic camera shooting from the same position. Also, the image and image sequences can be mined to analyse signalling behaviour across the flock and to track individual birds. AWARE-2 microcamera control modules use custom electronic modules (Supplementary Information, section 3) to buffer approximately ten image frames locally and to capture asynchronously and transfer individual microcamera images at up to ten frames per second.

An example HDR image is shown in Fig. 3. The brightness of this scene varies from regions of fully sunlit flat surfaces and bright sky to areas of deep shadow. An auto-exposure algorithm adjusts the exposure time for each individual microcamera to maximize the usage of the 8-bit dynamic range in each sensor. When the images are composited into the final scene, knowledge of the exposure setting is combined with the measured pixel values to estimate the source radiance with a global 32-bit dynamic range. Displays are typically limited to 8-bit output, so this HDR result must be mapped onto this smaller dynamic range. Figure 3 was generated by tone-mapping the HDR image.

[1]Fitzpatrick Institute for Photonics, Duke University, PO Box 90291, Durham, North Carolina 27708, USA. [2]ECE Department, University of Arizona, PO Box 210104, Tucson, Arizona 85721, USA. [3]Distant Focus Corporation, PO Box 7857, Champaign, Illinois 61826, USA.

Figure 1 | Pungo Lake as captured using AWARE-2. The total FOV is 120° by 50° and the composite image here consists of 0.96 gigapixels, where each pixel has an instantaneous FOV of 38 μrad. The measured values are logarithmically mapped to make better use of the display dynamic range. The relative responsivities of the individual microcameras were adjusted iteratively to minimize variation across sub-image boundaries. The labelled regions are referred to in Fig. 2.

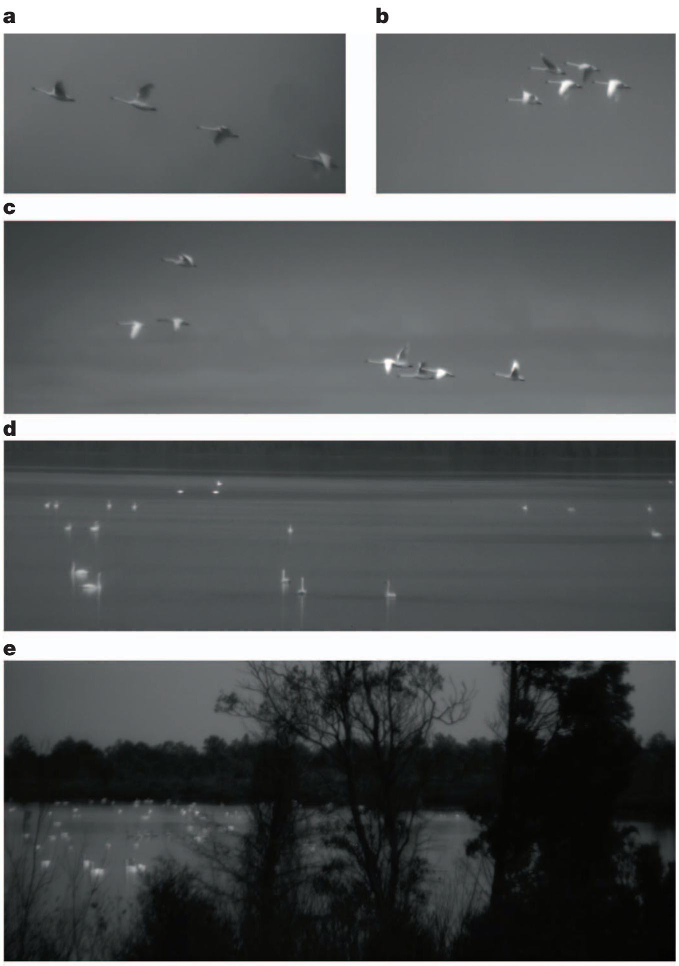

Figure 2 | Details of Fig. 1. a–e, Labelled regions in Fig. 1. The swans in **c** are 114 pixels long and are 310–350 m from AWARE-2. Each pixel corresponds to 13 mm at the position of the swans. In **d**, the most distant bird is 17 pixels long and the closest is 70 pixels long. The limited depth of focus of the camera is illustrated in **e**, where regions of the foreground foliage are in sharpest focus.

Tone mapping creates an individual 32-bit/8-bit conversion for each pixel in the scene, but ensures that the mappings vary smoothly from pixel to pixel[14]. The majority of the display dynamic range is used on shadows and highlights, with mid-tones compressed. The tone-mapped image more accurately matches human visual processing because our vision is foveated and our pupils adjust as we examine different regions of a wide field. More details on the compositing process are provided in Supplementary Information.

The maximum pixel count for an imager with aperture diameter A and the mean operating wavelength λ is $S = \pi A^2 \sin^2(\mathrm{FOV}/2)/\lambda^2$ (ref. 2). For AWARE-2, FOV = 120° and A = 16 mm, corresponding to a limit of two gigapixels at an operating wavelength of 550 nm. At its design capacity of 220 microcameras, a fully populated AWARE-2 would capture three gigapixels but the estimated field would decrease to two gigapixels after sensor regions with limited illumination had been removed and overlapping regions had been merged. AWARE-2's resolution is illustrated by the star field shown in Fig. 4, which shows details of a gigapixel sky survey with an exposure time of 1.85 s. Faint stars in this image illuminate two to four pixels after median filtering to remove hot pixels and logarithmic intensity mapping to fill the display dynamic range. We anticipate that higher-resolution multiscale systems with terrestrial motion compensation and microcamera adaptive optics to remove atmospheric blur may be developed for space situational awareness.

As shown in systematic resolution images and modulation transfer function measurements presented in Supplementary Information, section 4b, most of the blur in the star field image is due to defects in AWARE-2's microcamera lenses. To allow low-cost gigapixel array integration, AWARE-2 uses injection-moulded plastic relay optics. These lenses may be moulded with aspheric surfaces, requiring fewer elements and consequently less volume and mass than a spherical glass-element camera with similar performance. However, birefringence in the fabricated optics due to residual stresses introduced during moulding degrades AWARE-2's image quality and resolution relative to fundamental limits. We expect newer high-index plastics that minimize birefringence to enable the camera to approach these theoretical limits. We have also built glass microcamera lenses and, as shown in Supplementary Information, section 4c, AWARE-2 achieves pixel-limited optical resolution with these lenses.

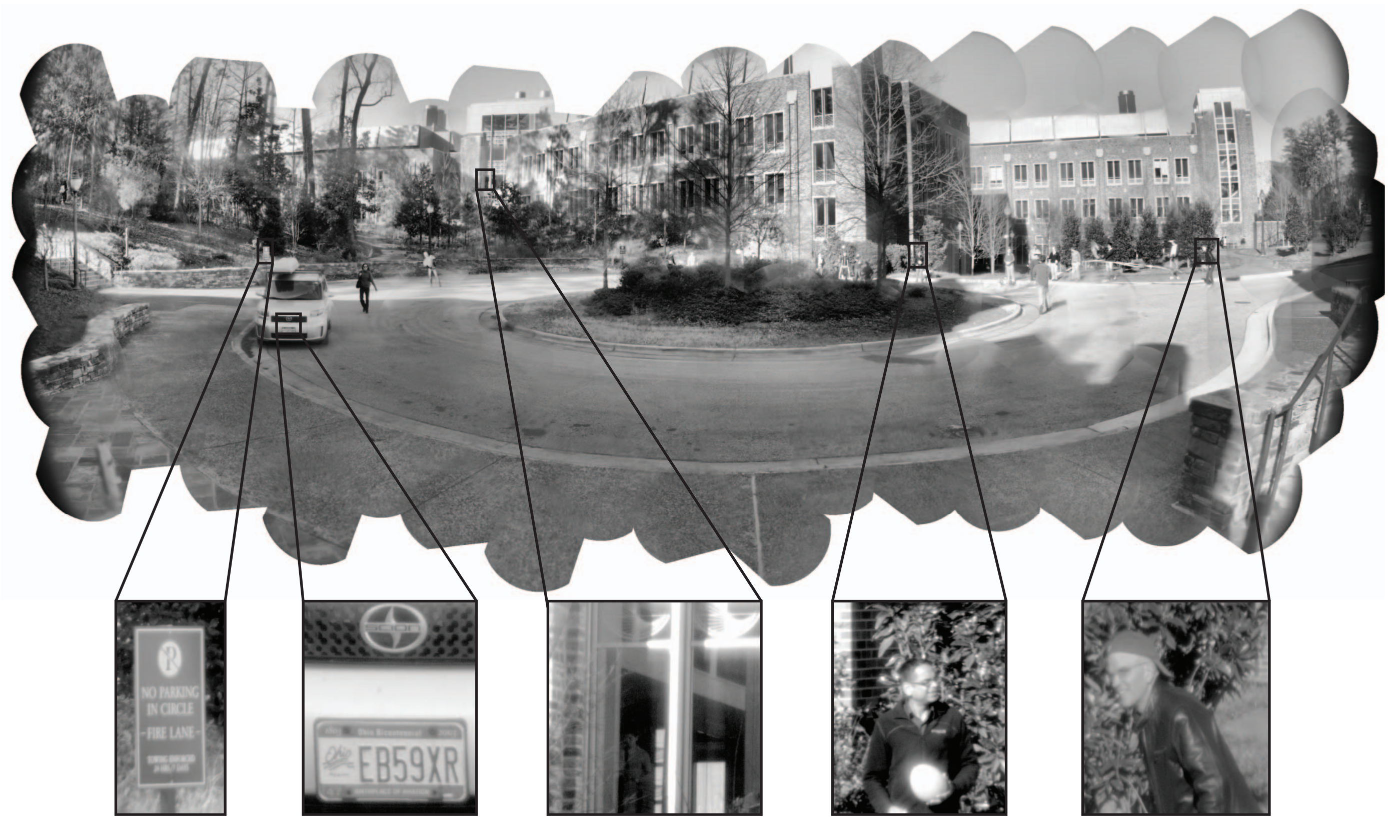

Figure 3 | Traffic circle captured using AWARE-2. Insets are digitally magnified by a factor of 13. Distances to the inset regions range from 15 m ('no parking' sign; first from left) to 92 m (detail of building; third from left). The exposure time for each microcamera was set independently of the others, and a tone-mapping algorithm was used to convert the resulting HDR image for display. Global distortion associated with mapping the 120° horizontal field onto a flat image is apparent.

AWARE-2 demonstrates that the age of ever-increasing pixel count is far from over. Although development of high-performance, low-cost microcamera optics and optomechanics have been the main challenge in the present stage of multiscale camera development, integrated circuits, rather than optics, remain the primary barrier to ubiquitous high-pixel-count imaging. To accommodate the electronics and allow for heat dissipation (the camera expends 430 W during image acquisition), AWARE-2 is mounted in a 0.75 m × 0.75 m × 0.5 m frame. The optical system occupies less than 3% of the system volume. The size of the camera is dictated both by the size of the electronic control boards and the need to cool them effectively. As more efficient and compact electronics are developed, hand-held gigapixel photography may become an everyday reality.

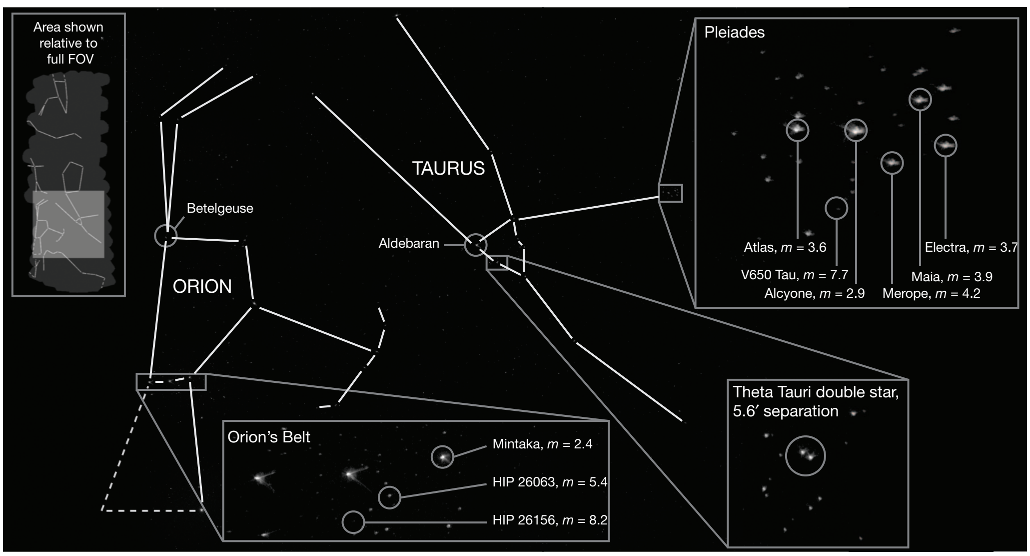

Figure 4 | Details of a star field captured using AWARE-2 with a 1.85-s exposure time. Image data was logarithmically mapped to display values to make better use of the available display dynamic range. Stars with apparent magnitudes of $m < 8.2$ mag are visible in the image. However, those with $m \leq 3.5$ mag saturate the detector at this exposure time.

METHODS SUMMARY

In Figs 1 and 2, all microcameras were set to focus at infinity and had a fixed exposure time of 232 μs. The image was captured on 5 December 2011 at 10:43. Figure 3 was captured using independent auto-exposure and auto-focus in each microcamera. The image shows the Fitzpatrick Center at Duke University on 18 January 2012. In Fig. 4, all microcameras were set to focus at infinity and had a fixed exposure time of 1.85 s. The camera was pointed at a right ascension of 4 h 59 min 2 s and a declination of 37° 05′ 45′′ and was located at 36° 00′ 50.24′′ N, 79° 00′ 13.38′′ W. Cloud cover was near zero. The typical sky brightness at this location is 19.50–18.38 mag arcsec^{-2} in the V band (Bortle scale of approximately 6). The image was captured on 15 January 2012 at 21:44:54 local time.

Auto-exposure initialization requires several seconds and updates in every third frame thereafter. The algorithm steps exposure up and down in logarithmically spaced increments until 1–3% of the pixels are saturated. After exposure is set, the focus motor is stepped in fixed increments. The focus metric is the soft-thresholded sum of the absolute value of the horizontal and vertical gradients independently evaluated over a region of interest, typically a 1,024 × 1,024-pixel image centre. Soft-thresholding sets gradient values below a fixed bias to zero, thus emphasizing sharper features. The step direction reverses when the metric at the present position exceeds the metric at the last position. Focal adjustment stops when reverses occur in three subsequent steps or when eight reverses occur in total. Focus resumes if the metric exceeds 30% of the stored minimum value. If the number of saturated pixels leaves the 1–3% target range, auto-exposure and focus reset.

AWARE-2 was pointed at clear sky with a diffuse plastic dome over the gigagon lens location, to calibrate each pixel's gain and illumination. In all figures shown, variable pixel gain and illumination was removed by 'flat-field correction'.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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