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Rosette-scan tomographic single-pixel imager

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Spin-scan tomographic scanning imagers utilise a reticle with a fixed number of thin slits and nutating optics, and have produced images and video at both infrared and optical wavelengths. However, the fixed nature of these systems reduces their versatility by restricting changes that can be made after manufacture. An alternative rosette-scan tomographic scanning imager based on similar concepts is proposed to overcome this limitation. A single thin-slit reticle is rotated to be perpendicular to the line scan angle of each rosette petal, thereby allowing tomographic reconstruction. The parameters of the proposed system can be dynamically changed to achieve different trade-offs between resolution and frame rate. Initial results obtained from a proof-of-concept prototype demonstrate the feasibility of this approach.

Introduction: Recent developments in single-pixel imaging have advanced the fields of medicine, military imaging and engineering. These imaging systems make it possible to capture images at various wavelengths at a low cost. The cost of high-resolution imaging systems at wavelengths other than the optical spectrum is generally dominated by the cost of the sensor array which makes such systems impractical [1–3].

It has been shown that single-pixel imagers can produce images and video with good resolution and frame rates using post-processing techniques such as compressive sensing (CS) and tomography [4, 5]. Single-pixel imagers that operate at a variety of wavelengths have been demonstrated, including in the infrared (IR) to terahertz spectra [6–8]. The majority of research on single-pixel imaging has focused on systems using digital micromirror devices (DMDs) or liquid-crystal displays (LCDs) to modulate the reflected or radiated light of an illuminated scene, and the use of CS to reconstruct an image. A number of samples of various structured light patterns are taken, after which an algorithm is used to reconstruct the image. In general, the resolution of the image for fixed image size improves as more samples are taken. Furthermore, pulsed lasers can be used to include the time of flight data to reconstruct three-dimensional (3D) images based on CS or tomography [9, 10]. The cost of these systems was dramatically reduced compared to systems with multiple pixels that achieve comparable resolution.

The resolution of single-pixel imaging systems is constrained by the size of the DMD array or LCD, so for example, a 256×256 pixel image can only be obtained using a 256×256 pixel device. While additional samples can improve the clarity of an image, the size of that image remains unchanged [11].

Additionally, the use of rosette-scan patterns with CS reconstruction has been considered [12, 13]. Rosette-scan systems move a narrow instantaneous field of view (IFOV) over the scene, as shown in Figure 2a, with the scan pattern (the number of petals) and the scan rate (the speed with which the IFOV moves) determining the clarity of the reconstructed image. Rosette-scan inherently emphasises the centre region of the scene, but there are applications where the majority of image information is assumed to be predominantly centred within the scene [13, 14].

A problem shared by all the single-pixel imaging systems considered above is the high computational cost of using CS to reconstruct images. One approach to addressing this problem is using tomographic reconstruction to generate images, as is done in Hovland's tomographic scanning (TOSCA) single-pixel imagers [1]. Low-cost spin-scan TOSCA single-pixel imagers have been shown to capture useful images at visible and IR wavelengths using computationally-efficient tomographic image reconstruction [1].

A rosette-scan TOSCA single-pixel imager is proposed in an effort to combine the versatility of rosette-scan systems with the computational efficiency of tomographic reconstruction. Initial results obtained using a proof-of-concept prototype indicate that this proposed approach can both produce useful images and allow trade-offs between parameters such as resolution and update rate.

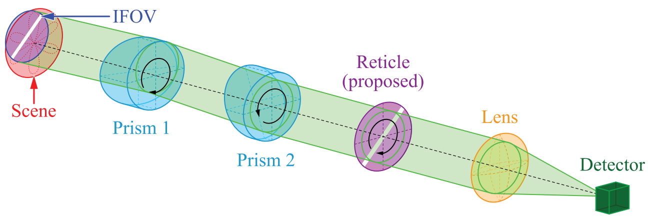

Fig. 1 *The proposed rosette-scan optical architecture. The IFOV would be smaller and the reticle would be absent for a traditional rosette-scan system [16] as seen in Figure 2a*

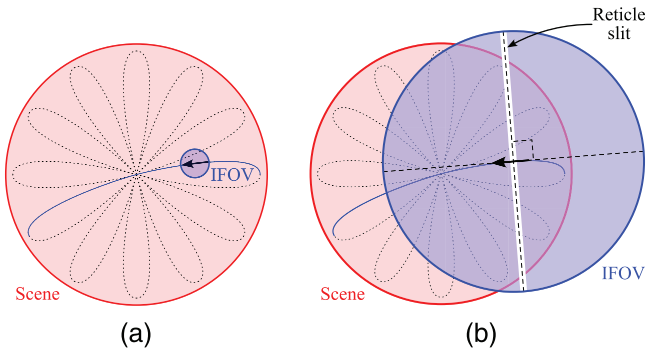

Fig. 2 *(a) The rosette pattern generated by the rotating prisms in Figure 1 with the IFOV of a conventional rosette-scan imager shown, and (b) the proposed rosette TOSCA concept showing how the reticle slit is swept across the scene*

Rosette-scan seeker: A rosette-scan seeker consists of a mirror-prism pair or a dual-prism pair [15], focusing optics, and a detector, as shown in Figure 1. The two prisms are rotated in opposite directions at different rotational velocities to obtain the rosette pattern. The relative rotational velocities of the two prisms determine the rosette pattern (e.g. the number, size, and spacing of the petals) [15] shown in Figure 2a.

It is known that a small IFOV is desirable in rosette-scan seekers to effectively distinguish between targets and decoys in the scene [15, 17]. A small IFOV would improve the signal-to-background-noise ratio. In general, one would choose a large number of petals to ensure that the entire scene can be observed. However, constraints on the speed of the rotating elements will limit the scan rate of the system, which affects the maximum number of petals, and subsequently, the size of the IFOV.

Rosette-scan seekers are also known as pseudo-imaging seekers due to the incorporation of spatial and temporal data to effectively track targets [18]. Increasing the amount of data sampled by, for example, increasing the number of petals will result in improved resolution. Additionally, incorporating CS to reconstruct the image results in an imaging system [12, 13].

TOSCA imager: The TOSCA imagers proposed by Hovland are based on sampling a scene in a manner that allows computationally-efficient tomographic reconstruction techniques to be used to form images [1]. This was achieved by using a combination of spinning optics and a reticle with narrow slits to sample a scene by sweeping a narrow slit across the scene at different angles in a manner similar to other tomographic systems [19]. The spinning optical system is similar to that found in older missile seekers, allowing mature technologies to be exploited. This, in addition to the reduced computational requirements associated with tomographic imaging, means that TOSCA imagers offer the possibility of low-cost implementation.

One significant drawback of a TOSCA imager is that system parameters such as resolution and update rate are largely determined by the physical construction of the system. As a result, reconfiguration of the characteristics of a TOSCA imager is only possible by changing part of the hardware. Additionally, the spin-scan TOSCA imager prototype implemented by Hovland showed that there are physical limitations on the number and angle of the reticle slits in a practical system [5], thereby limiting the practically achievable imaging performance.

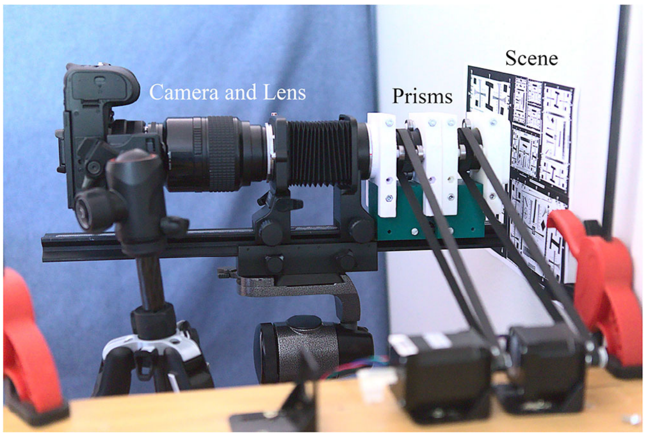

Fig. 3 *A photograph of the proof-of-concept prototype of the rosette-scan TOSCA single-pixel imager*

Specifically, the reticle structure is rather large radially, and increasing the IFOV or the number of angles at which the thin slit is swept across the image, would further increase the radial dimensions of the system.

Rosette-scan TOSCA imager: A rosette-scan TOSCA imager seeks to combine the versatility of a rosette-scan imager with the simplified reconstruction of a TOSCA imager. The result is a reliable and configurable single-pixel imager based on mature technologies and constructed with low-cost hardware. The relevant concept can be realized by noting that the IFOV of a rosette-scan imager need not necessarily be small, but can be large relative to the scene as shown in Figure 2b. The rosette-scan concept nutates the IFOV over the scene in a rosette pattern with the addition of a thin-slit reticle as shown in Figure 1. As in the case of TOSCA imagers, this configuration results in a narrow slit being swept across the scene, allowing tomographic reconstruction to be used.

The nature of the proposed rosette-scanning TOSCA concept is that variations to the rosette pattern can be made without fundamentally affecting the hardware or reconstruction processes. As a result, it is possible to dynamically adjust the operation of the system to different requirements such as resolution or update rate by simply changing the rotation rates of the prisms and the reticle, and the parameters of the tomographic reconstruction algorithm. So for example, the system could be configured to use a small number of rosette petals to provide a rapid update rate until an object of interest is encountered, at which point, the number of petals could be increased to provide higher resolution to better identify the object.

Experiment description: The simple proof-of-concept rosette-scan TOSCA single-pixel imager shown in Figure 3 was implemented and tested, with image reconstruction being implemented in MATLAB R2023a. The full optical system was implemented, with the exception of the narrow-slit reticle, which was simulated.

Similar to the seeker optics illustrated in Figure 1, the optics for this experiment consisted of two wedge prisms, both with a deviation angle of 4°. Each prism was placed into a 3D-printed rotor fastened with other 3D-printed structures, which was fixed onto a Nikon Bellows PB-6. The bellows ensured that each element was on the system's optical axis. Stepper motors rotated the prisms by use of a belt.

A digital single-lens reflex (DSLR) camera and lens were used to capture and focus the scene. A video of the nutating IFOV of the rosette-scan TOSCA system during operation was recorded. The `imregcorr` function was used to analyse the recorded video to determine the nutation position of the IFOV for the duration of the imaging process. Then, the line scan angle of each rosette petal was determined, and the simulated reticle mask was rotated to the specific angle and applied to the recorded frames, as seen in Figure 4. The nutating IFOV was then multiplied by the simulated reticle mask and averaged to obtain a single value, simulating a single detector device. A reticle mask width of 2 pixels was implemented to obtain the results in Figure 5, although a far larger reticle mask width is shown to illustrate the concept. The averaged intensity of the frame is determined and used to populate the

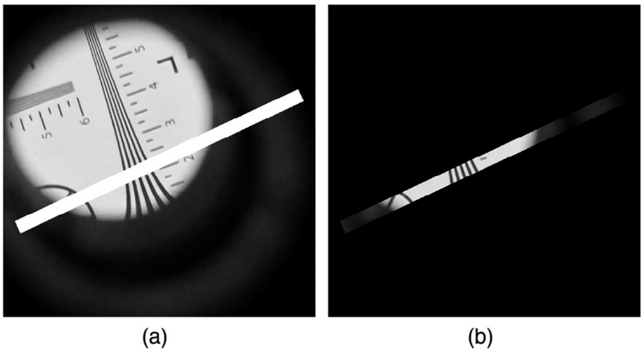

Fig. 4 *A thin-slit reticle is simulated by (a) masking a portion of the image to obtain (b) the portion of the image would be transmitted through the reticle*

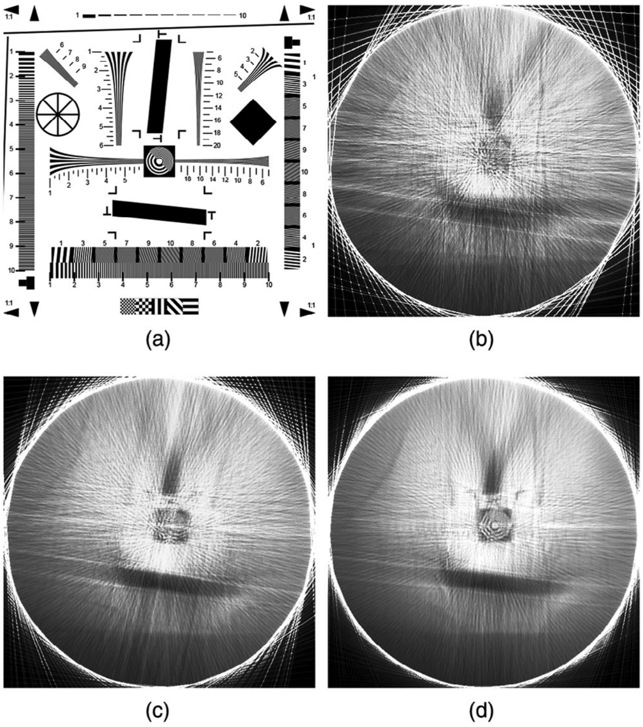

Fig. 5 *Reconstructed images of (a) a test image when (b) 40, (c) 80, and (d) 140 petals were used*

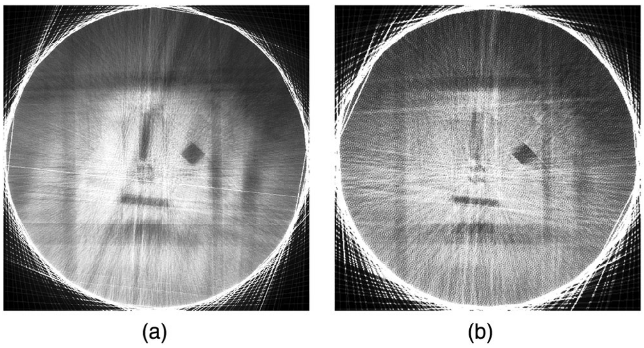

Fig. 6 *Reconstructed images with resolutions of (a) 882×882 pixels and (b) 444×444 pixels when the scan rate in (a) is doubled to produce (b)*

intensity function [19]. Filtered back projection was implemented to reconstruct the final image [20].

The frame rate of the DSLR camera and the prism pair rotational velocities could be controlled to complete a scan of the scene within a specified duration. The prism pair rotational velocities were set to be relatively slow to obtain a sufficient number of samples for each line scan due to the limited frame rate of the camera. The images in Figure 6 show a significant change in image size with varying scan rates.

The contrast of the images produced by the prototype were equalised using the `histeq` function in MATLAB R2023a to make the results of the imaging easier to view when printed.

The central portion of the ISO 12233 resolution test chart was used as a test target due to its combination of coarse and fine detail [21].

Results and discussion: The first illustration of the capability of the rosette-scan TOSCA single-pixel imager was to demonstrate the effect of the number of petals in the rosette pattern. The results were recorded with the same frame rate, imaging scene, and optical configuration. In Figure 5, it can be observed that an increase in the number of petals greatly increases the clarity and apparent image quality. This observation is consistent with the results obtained in TOSCA-related literature [5]. Furthermore, it can also be observed that the centre of the reconstructed image exhibits excellent resolution, with the objects near the edge of the reconstructed image frame being degraded like other rosette-scan imagers. An indication of this phenomenon is the solid black vertical rectangle above the centre which is accurately reproduced near the centre and fades toward the edge of the reconstructed image. These artefacts are inherent in the scanning method that was implemented and were not observed in existing TOSCA imagers making use of different scanning methods [5].

Although the clarity of Figure 5b is worse than the other results, it is still possible to identify a square object in the centre of the image and a larger rectangular object below it. Increasing the number of petals from 40 to 80 petals in Figure 5c and 140 petals in Figure 5d, improves the clarity of the centre square and more clearly captures the central circular pattern and other fine detail surrounding it.

The line artefacts seen in Figure 5 are inherent in tomographic reconstruction. The greater the number of distinct line scan angles, the fewer such artefacts will appear [6, 19]. The sampling space of the filtered back projection reconstruction process is non-Cartesian, while the displayed image is fundamentally in Cartesian space, and interpolation errors that also contribute to the artefacts arise [19]. Furthermore, any errors in the position of the centre of the IFOV could cause additional artefacts. It is also possible that the reticle mask is not perfectly perpendicular to the line scan, effectively incorporating unwanted data into the sampled intensity value. The fact that the centre of the image is distinguishable, but not the rest of the image is due to line-scan angle calculation errors. The slightest erroneous angular variation in postprocessing will cause the edges of the image to distort and appear to be out of focus. However, the centre of the reconstructed image remains unaffected by erroneous line-scan angle calculations.

The dynamic reconfigurability of the rosette-scan TOSCA single-pixel imager is shown in Figure 6, which considers a larger portion of the test image in Figure 5a than Figure 5. Figure 6a was captured with 80 petals resulting in an image of 882×882 pixels. Figure 6b was captured with the same parameters as Figure 6a, but with double the scan rate, resulting in an image of 444×444 pixels. Figure 6a clearly has a higher resolution than Figure 6b, but Figure 6a requires twice as much time to capture and generates twice as much data as Figure 6b.

Conclusion: A rosette-scan TOSCA single-pixel imager was proposed, with a proof-of-concept prototype demonstrating that useful images can be produced. The number of distinct line scans was shown to improve the quality of the reconstructed images. Furthermore, the ability to dynamically alter the scan pattern of a rosette-scan TOSCA imager was both introduced and experimentally demonstrated. For example, it was shown that the same imager could be dynamically reconfigured to trade the clarity of the resulting images off against the rate at which updated images were generated. Although some image degrading artefacts unique to the proposed scanning method were observed, these artefacts were caused by limitations of the proof-of-concept prototype rather than any fundamental limitation of the underlying concept.

Author contributions: Armand Duvenage: Conceptualisation; Investigation; Software; Visualisation; Writing – original draft. Warren du Plessis: Software; Supervision; Visualisation; Writing – review & editing.

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References

1 Hovland, H.: Tomographic Scanning Imagers. University of Oslo, Oslo (2016)

2 Gibson, G.M., Johnson, S.D., Padgett, M.J.: Single-pixel imaging 12 years on: a review. *Opt. Express* **28**(19), 28190–28208 (2020)

3 Lu, T., Qiu, Z., Zhang, Z., Zhong, J.: Comprehensive comparison of single-pixel imaging methods. *Opt. Lasers Eng.* **134**, 106301 (2020)

4 Kilcullen, P., Ozaki, T., Liang, J.: Compressed ultrahigh-speed single-pixel imaging by swept aggregate patterns. *Nat. Commun.* **13**(1), 7879 (2022)

5 Hovland, H.: Experimental tomographic scanning (TOSCA) imagers. In: Infrared Technol. Appl., pp. 150–155. Baltimore, Maryland (2014)

6 Hovland, H.: Construction and demonstration of a multispectral tomographic scanning imager (TOSCA). *Opt. Express* **21**(4), 4688–4702 (2013)

7 Chan, W.L., Charan, K., Takhar, D., Kelly, K.F., Baraniuk, R.G., Mittleman, D.M.: A single-pixel terahertz imaging system based on compressed sensing. *Appl. Phys. Lett.* **93**(12), 121105 (2008)

8 Bian, L., Suo, J., Situ, G., Li, Z., Fan, J., Chen, F., et al.: Multispectral imaging using a single bucket detector. *Sci. Rep*. **6**(1), 24752 (2016)

9 Kingston, A.M., Pelliccia, D., Rack, A., Olbinado, M.P., Cheng, Y., Myers, G.R., et al.: Ghost tomography. *Optica* **5**(12), 1516–1520 (2018)

10 Zhang, Y., Edgar, M.P., Sun, B., Radwell, N., Gibson, G.M., Padgett, M.J.: 3D single-pixel video. *J. Opt.* **18**(3), 035203 (2016)

11 Stojek, R., Pastuszczak, A., Wróbel, P., Kotyński, R.: Single pixel imaging at high pixel resolutions. *Opt. Express* **30**(13), 22730–22745 (2022)

12 Uzeler, H., Cakir, S., Aytaç, T.: Image reconstruction for single detector rosette scanning systems based on compressive sensing theory. *Opt. Eng.* **55**(2), 23108 (2016)

13 Stoltz, G., Stolz, M.: Performance estimation of a real-time rosette imager. *Proc. SPIE* **11537**(11), 115370D (2020)

14 Phillips, D.B., Sun, M.J., Taylor, J.M., Edgar, M.P., Barnett, S.M., Gibson, G.M., et al.: Adaptive foveated single-pixel imaging with dynamic supersampling. *Sci. Adv*. **3**(4), e1601782 (2017)

15 Jahng, S.G., Hong, H.K., Choi, J.S., Han, S.H.: Reticles: Nutating Systems. In: Hoffman, C., Driggers, R. (eds.) *Encyclopedia of Optical and Photonic Engineering*, 2nd ed., pp. 2789–2800. CRC Press, Boca Raton, FL (2015)

16 Neri, F.: *Introduction to Electronic Defense Systems*, 3rd ed. SciTech Publishing, Rayleigh (2018)

17 Jahng, S.G., Hong, H.K., Han, S.H., Choi, J.S.: Design and analysis of improved instantaneous field of view of rosette scanning infrared seeker. *Electron. Lett.* **33**(23), 1964 (1997)

18 Deyerle, C.M.: Reticles: missile seekers. In: Hoffman, C., Driggers, R. (eds.) *Encyclopedia of Optical and Photonic Engineering*, 2nd ed., pp. 2780–2788 CRC Press, Boca, Raton, FL (2015)

19 Hsieh, J.: *Computed tomography: principles, design, artifacts, and recent advances*, 2nd ed., Wiley Interscience, Hoboken, NJ (2009)

20 Hovland, H.: Tomographic scanning imager. *Opt. Express* **17**(14), 11371–11387 (2009)

21 Westin, S.H.: ISO 12233 test chart. Accessed June 1, 2023. https://www.graphics.cornell.edu/westin/misc/res-chart.html (2010).