Simplest stereo view of TEM images

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Abstract

In this short communication, the authors wish to remind an old but largely forgotten method of stereo view in TEM. It is possible to perceive TEM images stereoscopically without any technical equipment, which might facilitate the return of stereo methods in the active arsenal of electron microscopists.

During the last decades in Transmission Electron Microscopy (TEM), significant efforts were made in 3D imaging of nanoscale objects [1]. For example, electron tomography typically involves collection of a tilt series consisting of 100 - 200 images followed by the reconstruction of a 3D object with a variety of techniques. Tomography belongs to one of the most complicated TEM methods demanding huge experimental efforts and intensive image processing. Electron tomography is prone to be affected by numerous instrumental and reconstruction issues, which stimulated the development of a tremendous family of various technique modifications and reconstruction algorithms to minimize artifacts.

In this communication, we would like to remind that a much simpler method to retrieve the 3D arrangement of nanoscale objects might be sufficient in many cases. Some higher animals (including humans) are capable of *stereoscopic view*, i.e. ability to recognize essential features of 3D objects from just two views taken under the slightly different perspectives of their eyes. In the field of TEM, this ability would mean that just one moderate tilt of an object in the microscope might provide sufficient information to reconstruct at least some of its 3D geometry.

The idea of stereo TEM imaging is quite old. In fact, the implementation of a sample tilt in early electron microscopes of 20th century was partially motivated by the wish to gain a stereo viewing facility [2], at that time standard for light microscopy. TEM stereo imaging was quite common in biology [3] but also found its niche in material science, for example in studies of defects like dislocations [4] loops and voids formed in radiation damage [2, 5] and for visualization of mesopores in zeolite [6]. In the closely related area - Scanning Electron Microscopy (SEM), the stereoscopic methods were used as well [7]. However, the practical skills of stereo imaging were largely lost [2] after the atomic-resolution paradigm became dominant in TEM. The High-Resolution TEM (HRTEM) was very sensitive to small tilts and, more importantly, the contrast formation in HRTEM appeared to be hardly compatible with the perception mechanism hardwired in human brains. Nevertheless, techniques of stereo imaging might be very useful for medium resolution TEM work, which is still highly required in certain areas like biology, mineralogy and environmental studies.

Fig.1 shows an example of a so-called stereo pair consisting of two images of a 2D net composed of Au nanowires. The images were taken under a 14.4° difference in α-tilt. In order to fit the human ability of stereo perception, both images were rotated so that the direction of the α-tilt became horizontal. Furthermore, the images were cropped to a circular shape as the arbitrary tilted rectangular shapes might confuse the perception. Finally, we added two sharp black fix points facilitating the fusion of both images into one stereo view. The stereoscopic view allow to detect clearly the bending of the 2D network in different directions.

The key question is how to view such stereo pairs in order to achieve 3D perception. This often involve various equipment ranging from colored/polarised glasses or binocular stereoviewers to assessors of virtual reality. Those became recently quite common in gaming community but are still rather an exception in research labs. Therefore, the necessity of any, even simplest, devices hampers the broad spreading of stereo view practice among electron microscopists.

In the present communication, we consider the techniques allowing to perceive stereoscopic view *without* any technical equipment. Although a certain initial training might be required, such ability would then allow for stereo perception in any situations, just looking at a stereo pair at flat paper or standard monitor. In the past, students of cartography were obliged to practice such stereo view in order to perceive topographic stereo maps, but in our days it is less common. The regular practicing of these techniques could facilitate the return of stereo vision in the active arsenal of electron

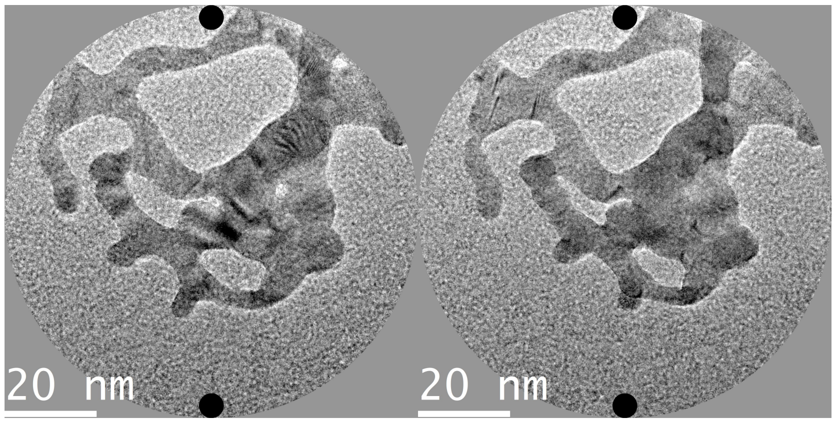

Figure 1: Stereo pair consisting of two images of Au networks, i.e a 2D net composed of Au nanowires. The images were taken under a 14.4° difference in α-tilt. To obtain stereo perception, it should be viewed with the divergence technique as shown in Fig. 2a. *Note that the physical width of the pair should not exceed 120 mm on paper or monitor for this viewing technique.* The same image can be viewed with the crossing technique (Fig. 2b) although the resulted 3D object will be mirrored in the depth dimension. The later technique allows to enlarge the physical size of the stereo pair to any desirable value.

microscopists.

The easiest way to perceive a 3D object from a stereo pair is to diverge your view as shown in Fig. 2a:

1. Look normally at the stereo pair. Choose the distance between eyes and the paper (monitor) most comfortable for viewing.
2. Try to glance "behind" the monitor. If this sounds not easy, place the stereo pair near the monitor edge such as you can easily move your view at some distant objects. The images perceived by the left and right eyes start to split. One is moving to the left, another to the right.
3. Tune the appearance of two splitting images such as they form a kind of a "trio" of images as shown in Fig. 2a. The marker points at the upper and lower edges of the central image must coincide precisely. Tilt the head a bit if necessary. Suddenly, your brain will start to perceive the central image in the trio as a 3D object.

It is clear from Fig.2a that the divergence method put certain restrictions on the physical size (on paper or on computer monitor) of a stereo pair. The angle δ under which the observer normally inspects images is

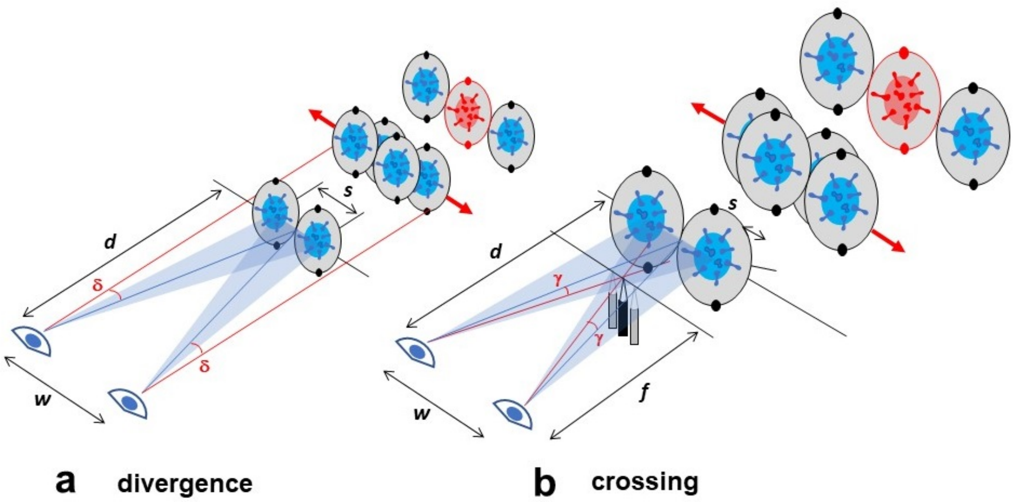

Figure 2: Two ways of viewing stereo pairs: (a) divergence of eyes and (b) crossing eyes. Blue rays represent "normal" view while red rays demonstrate how the viewing directions should be changed to provide 3D perception. Viewing beams for two eyes are shown by the red lines. In both viewing techniques, two images in a stereo pair are seen as a row of three images where the central image delivers stereo view.

$$\delta \approx \frac{w}{2d} \quad (1)$$

where d is a distance between a paper (monitor) and eyes and w is an inter-pupillary distance, which is 62-64 mm for humans in average. The maximal observable shift ν of an image when diverging eyes into the parallel view is

$$\nu \approx \delta d \quad (2)$$

As both the images must be shifted at $s/2$ towards each other, from (1) and (2) it follows that s should be less or equal to w. Therefore, the total width of a stereo pair can not be larger than $2w$. In other words, the divergence technique is only applicable for small images whose physical width does not exceed 120-130 mm. This is probably not as dramatic limitation in the era of smartphones, when images are often viewed at small screens.

For the crossing technique, the eyes viewing beams should be tilted in the other directions as shown in Fig 2. The observable shift can be deduced as:

$$\nu \approx (\gamma - \delta)d \quad (3)$$

where γ is defined by the minimal focal distance at which the observer can focus her/his eyes:

$$\gamma = \frac{w}{f} \tag{4}$$

As the observer is typically able to focus eyes at distance f comparable to interpupillary distance w, γ can reach one radiant. This means that the crossing technique is applicable for the broad range of the image sizes including presentations at a large screen in an auditorium. However, a crossing view requires in general more training in comparison to a divergence view. We recommend the following step sequence:

1. Look normally at the stereo pair. Place a sharp tip of a pen or a pencil on the way of your view as shown in Fig 2b. As you are focused at the distant images, you will see two pencil tips at that moment.
2. Tune the position of the pencil such as the left tip points to the center of the left image in the stereo pair and the right tip points respectively to the center of the right one (Fig. 2b). If necessary, tilt the head a bit.
3. Focus your view at the pencil. Two tips merge in one. Note that the images at the back view now form a "trio". Try to tune the central image in the trio such as the marker points coincide precisely.
4. Carefully move you attention from the pencil tip to the central image *without* loosing the angle between both beams of sight. Remove the pencil.

The disadvantages of such stereo view comparing to tomographic reconstruction are quite clear. First, it allows to visualize about half of a 3D object only as the back side is invisible for both images in a stereo pair. Second, the depth scaling depends on the acquisition and viewing conditions. The accurate perception of the depth dimension is only achieved if

$$d = \frac{w}{\Delta\alpha} \tag{5}$$

where w is, as before, the interpupillary distance, d is the distance to the paper (monitor) and $\Delta\alpha$ is the change in the α tilt of two images. For the typical inspection distance of 250mm and w = 62-64 mm, this suggests that best $\Delta\alpha$ is about 15°. When d deviates from (5), the perceived depth dimension would correspondingly deviate from the reality [1]. Still, these drawbacks might be not as crucial taking into account the ease of image acquisition and processing.

Furthermore, stereo view and tomographic reconstruction are not necessarily competitive techniques. One of the questions of tomography is how to display reconstructed objects in presentations [2]. Flat projections are not quite informative while videos with rotating 3D objects are not always technically possible. A couple of adequately chosen stereo views formed from the tomographic reconstruction could be an effective solution.

Except of the practical utility of TEM stereo view, the exercises described above might induce some general thoughts about 3D reconstruction. At the moment when the stereo view at two images is successfully achieved, the observer experiences a sudden and quite realistic 3D perception. This perception has even a certain tolerance - the head can be slightly moved or titled without immediate disappearance of the 3D perception. Of course, such a "reconstruction in brain", as any reconstructions, is not free of artefacts that in this case would be called optical illusions. Still, the reconstruction is processed by the brain almost instantly while the accuracy based on only two images is amazing [2]. Imitation of such performance by the existing computer technologies typically results in a rather complicated and slow code [8, 9]. The future of the image processing is commonly expected in developing sophisticated artificial networks. In that respect, the deep examination of how the visual reconstruction is actually processed in the natural networks might be very instructive.

More examples of TEM stereo pairs can be found in Supplementary Material. The open-source DigitalMicrograph plugin for making stereo pairs can be free downloaded at http://temdm.com/web/plugins/.

Acknowledgement

The authors appreciate very valuable comments from Prof. Archibald Howie, University of Cambridge who shared his opinion on the topic, also in historical perspective. The materials for TEM samples were kindly provided by A. Eychmüller, Technical University of Dresden, E. Sturm, University of

[1] This disadvantage may eventually turn to an advantage for some objects where the negligible variation of features with depth needs to be artificially enhanced.

Konstanz, M. Ruck, Technical University of Dresden and A. Fery, Leibniz Institute of Polymer Research Dresden. The support from ERC (grant 715620 under the Horizon 2020 program) is acknowledged.

Supplementary

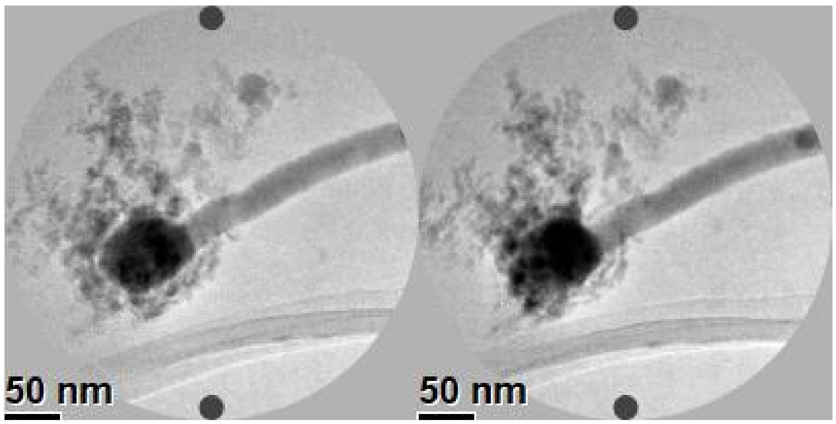

Figure 3: Stereo pair showing a BiRh nanowire growing from a round particle surrounded by the nebula of tiny stuff. The difference in α-tilt is 20.4°.

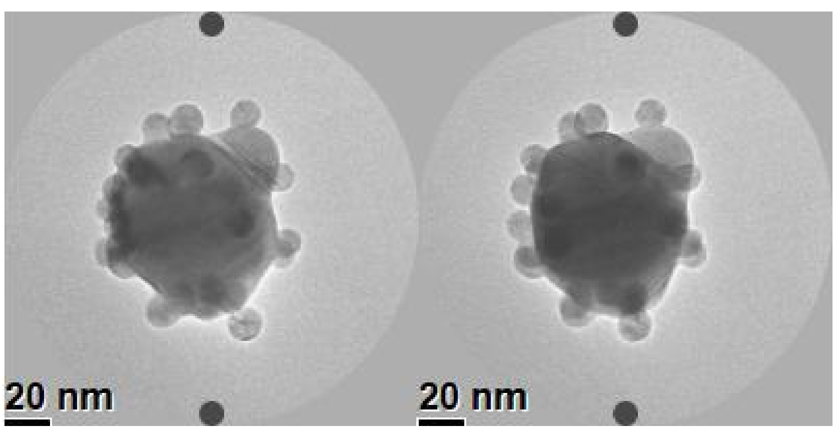

Figure 4: Stereo pair showing three connected Au particles decorated by smaller Au satellites. The difference in α-tilt is 14.8°.

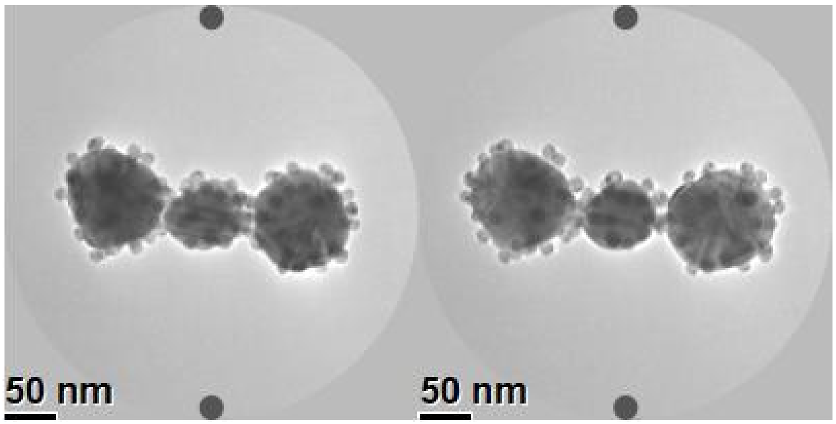

Figure 5: Stereo pair showing three connected Au particles decorated by smaller Au satellites. The difference in α-tilt is 19.5°.

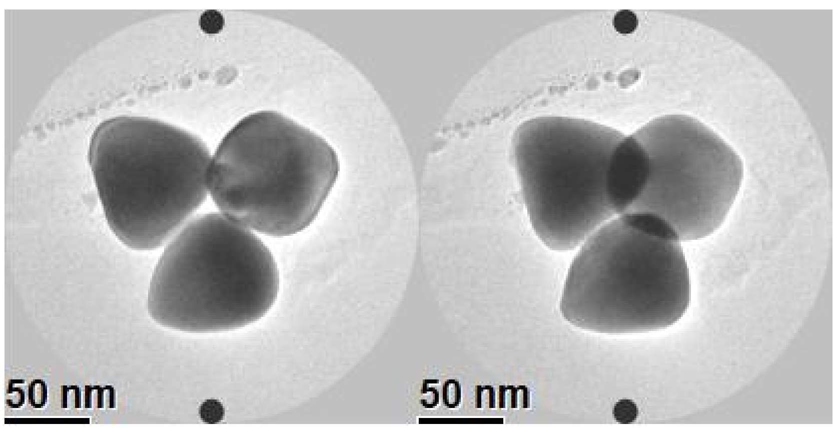

Figure 6: Stereo pair showing a agglomeration of three Au particles of nearly cubic shape. The difference in α-tilt is 22.0°.

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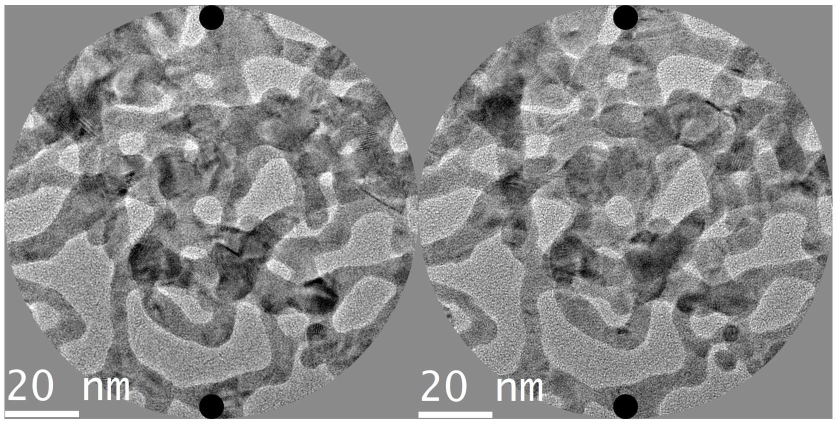

Figure 7: Stereo pair showing a debris of Au networks. The difference in α-tilt is 14.9°.

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