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Convolutional neural network as a tool for automatic alignment of electron optical beam shaping devices

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The evolution optics in electron microscopy has involved major steps, including the introduction of spherical aberration correction [1], chromatic aberration correction [2] and monochromators [3]. Each increase in complexity has resulted in an increase in the difficulty of instrument control.

One of the most significant recent developments is electron beam shaping through electron optical components based on microelectromechanical systems technology [4] that can be used to generate vortex beams [5], non-diffracting beams [6], compact aberration correctors [7] and quantum state analysers [8].

Although the basic concept of the operation of each lens and optical element is known, the overall behaviour of the microscope is not predictable in detail and the quality of microscope performance is limited by the skill of the user.

Here, we use a convolutional neural network (CNN) [9], which is able to learn from a large set of training images to extrapolate a detail or the value of a parameter tagged to each image [10]. The success of the technique is based on the fact that it permits any parametrical space to be treated, no matter how complex, provided that enough data are fed to the learning algorithm. It is also often more “robust” to noise than an analytical model.

We are motivated by the specific case of an orbital angular momentum (OAM) sorter [11], which makes use of electron beam shaping to measure an electron beam’s component of OAM in the propagation direction by decoupling the azimuthal and radial degrees of freedom.

The OAM sorter presents the added difficulty to be composed of two independent beam shaping elements. These elements are located in distinct planes of the microscope and must be accurately aligned with respect to each other. For this reason the OAM sorter can be considered as a test bench for other complex electron optical apparatuses.

The CNN has been trained on a dataset of 20000 computer generated images representing the point spread function of the OAM sorter in the presence of different aberrations. The images have been obtained using custom software.

After the training, the CNN is capable of determining parameters such as defocus and sorter electrode excitation from a single spectrum image. In order to validate the fitting accuracy of the CNN, the predicted misalignment coefficients were fed back into the simulation algorithm. The resulting images (Fig. 1, lower row) agree with the real images (upper row).

The fitting of an experimental image using the CNN was found to only take (on average over 1000 iterations) 56 ms on a conventional laptop, including image pre-processing. The computational time is therefore negligible compared to the acquisition time. For this reason, we anticipate that a CNN can provide real-time control and feedback about alignment accuracy during experiments.

We have demonstrated that a neural network can be used to determine alignment parameters for the complex electron optical configuration of an OAM sorter, for which the effects of misalignment cannot easily be managed analytically or adjusted manually. The fitting is demonstrated to be fast and reliable, opening the way to real-time automated control of the experimental setup.

The proposed method is not however limited to the OAM sorter. Such an approach can be applied in real time to align other complex optical systems, such as spherical aberration correctors, based on minimal experimental data. We envisage that in the future experimental devices will be able to self-diagnose and communicate with operators in real-time.

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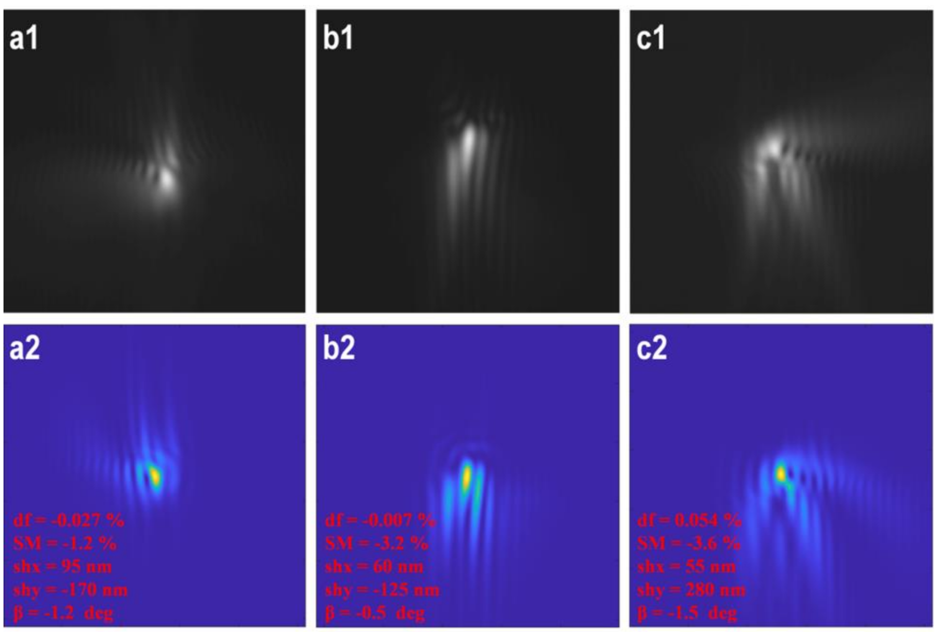

Figure 1. Demonstration of the predictive ability of the CNN for a comparison between experimental images (upper row) of the Sorter point spread function and simulations performed using the parameters predicted by the CNN (lower row). The fitted parameters, reported as labels, are defocus (df), sorter excitation (SM), beam shift (shx and shy), rotation angle (β).

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