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News & Views

Single-pixel imaging with high-energy electromagnetic radiation and particles

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High-photon-energy electromagnetic radiations in the forms of X-rays and γ-rays and particles such as neutrons and electrons are routinely used for various imaging and diffraction modalities with applications ranging from materials science and chemistry to biomedical imaging and industrial imaging. They provide important unique information on the structure and the functionality of the investigated samples that other methods cannot provide. However, despite the extensive efforts, there are several critical challenges that hamper further improvements in the performances of the modalities and thus limit the accessible information. Interestingly, while very different in the way high-photon-energy radiation and particles interact with the sample, imaging modalities that utilize them share similar challenges. Among the major challenges are damage to the sample when it is exposed to the probe beam and the limited resolution of the images (for electrons the resolution can be high but only for small samples). The origin of the damage is the large quanta of energy that is absorbed during the interaction between the probe and the sample. The resolution is limited since magnification and point-to-point imaging are very challenging with high energy photons and particles due to the limited available optics. For some applications, the sensitivity and the slow time response are also obstructive.

Traditionally, two approaches for imaging have been utilized. In the first approach, a wide beam irradiates the sample, and a pixelated detector is mounted after the sample to measure the intensity distribution of the transmitted or scattered beam. In the second approach, a focused beam is used, the sample is raster scanned, and most often a single-pixel detector is used to collect the transmitted or scattered beam after the sample.

In recent years, a novel method that utilizes structured illumination and correlation for the reconstruction of the shape of the sample has been developed [1]. Here a wide beam that is modulated either by a phase or by an amplitude mask hits upon the sample and is collected by a detector (it is also possible to modulate the beam after its passes the sample). The modulation leads to nonuniform intensity patterns at the plane of the object, and thus the intensity measured by the detector is proportional to the product of the modulated intensity and the transmission (or reflection depending on the geometry) of the sample. The closer the correlation between the intensity pattern of the beam and the transmission pattern of the sample, the higher the intensity at the detector. The measurement of the sample is repeated for various realizations of patterns in the beam by scanning the modulating mask, which contains different patterns at different positions. In the last step, the intensity at the detector is correlated with the patterns of the input beam and the shape of the sample is reconstructed using computational imaging algorithms [1].

The method requires that we know the patterns of the beam before the object for each of the realizations. Since optical components such as beam splitters are absent, this information is acquired either by measuring the mask patterns for all the realizations by a pixelated detector before the object is inserted, or by fabricating a mask with known patterns. Once the mask patterns and the beam properties are known, it is possible to calculate the patterns of the beam at the plane of the object. Alternatively, it is possible to mount the pixelated detector at the plane of the object and to measure the intensity at the plane of the object directly.

Since in many cases we need to measure only the total intensity after the sample, a single-pixel detector can be used for the measurement. In this case the method is often called "Computational Ghost Imaging" (CGI) or "Single-Pixel Imaging" (SPI) [1,2]. CGI was first realized with THz photons [3] and later with X-rays [4] electrons [5] and neutrons [6]. An illustration of a two-step CGI is shown in Fig. 1.

The important question is how we can use CGI to overcome the challenges of standard high-energy photon or particle imaging modalities. We address this question in the following discussion.

The spatial resolution of pixelated detectors is determined by the smallest feature that the detector can resolve. In many scenarios for electromagnetic radiation at high-photon energies and particles, the detectors rely on scintillation screens that convert the detected signal into visible photons, which are then detected by a visible-light camera. In this case, the resolution is determined by the blurring that the scintillator introduces, and it decreases with the thickness of the screen. Since on the contrary the detection efficiency scales with the thickness of the screens, there is fundamental tradeoff for those detectors between the efficiency and resolution. This tradeoff can be lifted using CGI since with this approach the detector is not required to exhibit a high resolution because the resolution is determined by the inhomogeneity of

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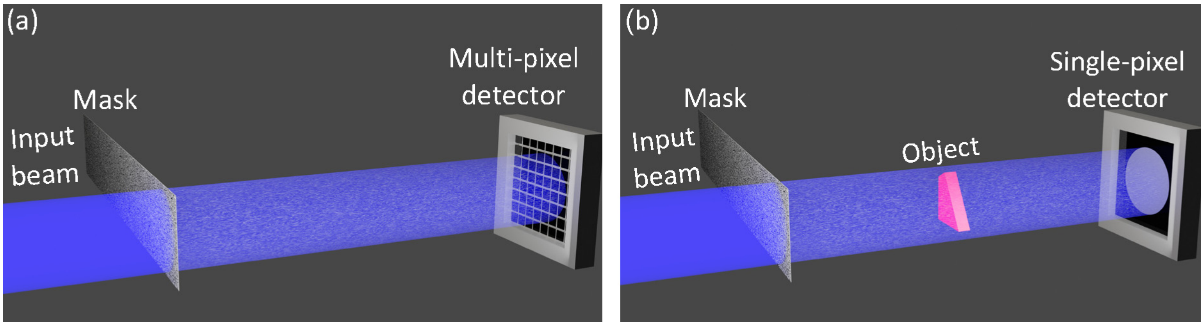

Fig. 1. (Color online) CGI experimental setup. (a) The calibration: the mask is characterized using a broad beam and a pixelated detector in the absence of the object. (b) The object measurement: the object is inserted, and the mask is scanned. The intensity at the single-pixel detector for the various positions of the mask is registered. If the mask is fabricated in a way that the patterns are known, only step b is required. In this case the resolution is determined by the feature size of the mask and can be higher than the resolution of standard pixelated detectors. In both cases the intensity patterns at the plane of the object are calculated from the knowledge of patterns of the mask, which are either measured or controlled by fabrication.

the beam [2]. In other words, in CGI the resolution is determined by the size of the feature of the mask that modulates the beam.

Another advantageous application of CGI is when spectroscopic information is important, for example for the measurement of the shape of fluorescing samples, or when a broad-spectrum input beam is used [7] or to retrieve kinematic information of scattered neutrons or electrons [5,8]. For example, X-ray fluorescence is used for the mapping of chemical element distributions in the inspected samples and neutron spectroscopy can provide information on the motion of the atoms, the rotational modes of molecules, and magnetic and quantum excitations. This information is hard to retrieve with multi-pixel detectors since the detectors are required to provide spatial and spectroscopic information at the same time and since the scattering of the radiation or the particles is nondirectional. One more potential advantage is the response time of a single-pixel detector, which is faster than the response time of a pixelated detector. This is important for measurements of fast dynamics and can be done as has been recently deconstrued with X-rays [9]. With this approach that works for periodic dynamics, the measurements that are conducted with the single-pixel detector are synchronized with the dynamics or the motion of the objects and the scan is performed as in standard CGI. At the end of the measurement the data are rearranged to reconstruct snapshots of the dynamics of the object.

Furthermore, it has been claimed that CGI can be used to mitigate radiation damage for the investigated samples that are radiation sensitive [10]. This has been explained by arguing that in the measurement of the object the single-pixel detector is used and that this type of detector can be used at lower doses since the noise scales with the number of pixels (for example in the case where each pixel exhibits a fixed amount of background noise). However, this claim is debatable and the answer to the question whether CGI can be used for dose reduction depends on the sparsity of the sample and on the source of the noise [11]. One way to understand this statement is to think of the single-pixel imaging as the following sequential measurement. If the image we want to reconstruct contains m pixels, this means that we have m unknown variables to find. We therefore need to perform m measurements to construct m equations to produce the image without ambiguities. Consequently, for a single realization where the intensity is indeed weak, the total amount of the dose after m realizations is equal to the dose in conventional imaging. Furthermore, this is true only when the realizations are orthogonal, that is, completely different, and in many scenarios this condition is not satisfied, thus the total dose is higher than with conventional imaging. The only way to reduce the dose is to reduce the number of realizations, and the only practical way to accomplish this reduction is by prior knowledge or by the fact that almost all objects in nature are sparse in some basis. The idea is analogous to compressed sensing but here it is an essential ingredient for the dose reduction. Indeed, recent algorithms have shown significant compression ratios by compressed sensing [12] or machine learning approaches [13,14]. With these new algorithms CGI can be used to mitigate sample damage owing to the interaction with the probe beam and to enable measurements with weaker sources. The latter is important since weaker sources are cheaper, more available, and require relaxed safety measures with respect to large bright sources. In their paper He et al. [8] show that the quality of the image that they acquired by CGI with a small number of neutrons was significantly improved when they used the effective convolutional neural network (CNN) algorithm [15]. This is an important step in the direction of developing single-pixel detection with neutrons. Further improvements in the algorisms would be very beneficial for the progress in this field.

Compressed sensing is also advantageous over raster scanning approaches since the number of scans with structured illumination that utilizes compresse sensing or machine learning is significantly smaller than the number of sampling points with raster scans. Therefore, it will enable faster scans and allow the measurement of large samples with extremely high resolutions.

Despite the impressive progress in recent years, which is mainly reflected in the demonstration of CGI with various systems, there are several challenges that have to be solved for further progress in CGI with high-energy photons and particles. The main challenge is the fabrication of masks that can efficiently modulate the beams since the modulation is proportional to the height of the patterns of the mask while the resolution is limited by the lateral size of the features. Unfortunately, with most fabrication techniques the aspect ratio (the ratio between the height and the lateral dimensions) is restricted, thus the progress in those technologies will have an important impact on the progress in this field. Another challenge is the measurement time, which is still relatively long. Improvements in the image reconstruction algorithms and with the scanning speed of the mask are necessary for practical applications. Other approaches to reduce the measurement time are replacing the single-pixel detector by an array of single-pixel detectors and using multiplexing [16] for example, by acquiring several realizations at different photon energies or kinetic energies simultaneously.

In conclusion, the novel approach of single-pixel imaging and CGI in particular is a promising approach for imaging with electromagnetic radiation at high-photon energies and with particles such as neutrons and electrons. It has the potential to overcome critical fundamental limitations of conventional imaging approaches and to lead to a novel technology that can provide more information than reachable today in a large range of disciplines.

Conflict of interest

The authors declare that they have no conflict of interest.

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