Intelligent and efficient dual-wavelength ghost imaging

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Abstract

Due to the scanning nature of ghost imaging and the inherent low light levels of quantum experiments, imaging speeds are rather unsatisfactory. To overcome this limitation, we leverage a two-step intelligent algorithm approach to establish an optimal early-stopping point for the experiment while preserving and maintaining the information contained in the image. Step one enhances the reconstructed image after each measurement and employs a deep-convolutional autoencoder, while step two recognises the image after each measurement by a neural classifier. We achieved a recognition confidence of 75% at 22% of the image reconstruction time, hence reducing the time 5-fold while preserving the image information. We tested our method on a dual-wavelength imaging system however, our procedure can be extended to many such systems that are of quantum nature.

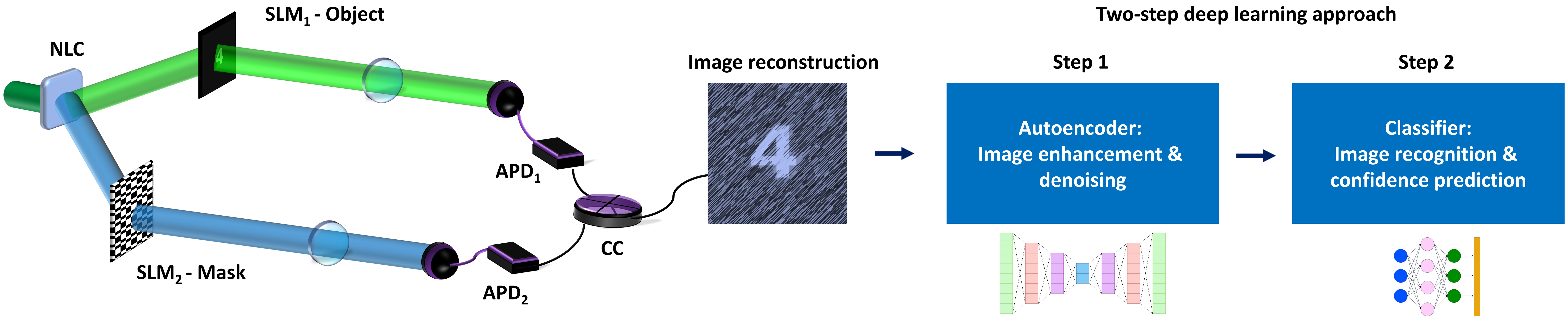

Figure 1: Dual-wavelength entangled photons are spatially separated along two arms. One photon interacts with the object and is collected by a bucket detector. The other photon is collected by a spatially resolving detector comprising a patterned mask and a bucket detector. The image is reconstructed by a linear combination of the patterned masks weighted by the coincidences. After each image reconstruction the image is sent to the autoencoder for enhancement and denoising and then to the classifier for recognition and confidence prediction.

Introduction

Entangled photon pairs are employed in quantum ghost imaging to facilitate an alternative image acquisition method. These photon pairs can be either degenerate or non-degenerate in nature [1]. Non-degenerate, or dual-wavelength, ghost imaging offers the ability to image with wavelength bandwidths where spatially resolving detectors are impractical. Due to the scanning nature (a series of binary intensity patterns or masks) and the inherent low light levels of quantum ghost imaging, imaging speeds are unsatisfactory [2]. Our two-step intelligent algorithms leverage a deep convolutional autoencoder network to enhance the reconstructed image after each measurement and a recognition algorithm to predict the confidence level of object recognition after each measurement, Reducing image reconstruction time by reducing the number of measurements needed. We demonstrate a 5-fold reduction in image acquisition time, leading to time-efficient ghost imaging. We believe that this novel two-step intelligent algorithm approach will provide valuable insight into time-efficient ghost imaging.

Intelligent algorithms, parameters and criteria

Step one – random noise was added to the training dataset until the entire dataset was completely distorted, a deep convolutional autoencoder was trained to extract noise and enhance the distorted dataset. Step two - a neutral classifier was trained to recognise the enhanced images from the dataset and to predict their confidence level (process shown in Fig. 2).

Procedure – the intelligent algorithms were trained pre-measurement to allow for instantaneous image enhancement and recognition post-measurement. The dual-wavelength experiment was performed and the image was saved after each reconstruction, i.e. after each mask (mask types and resolution shown in Fig. 3). Each image reconstruction was passed to our autoencoder for enhancement and denoising, followed by our classifier for recognition and confidence prediction. The output is a confidence curve (shown in Fig. 4) which we used to determine our early stopping point. A strict criteria of 75% confidence was imposed before stopping the experiment, 50% confidence is generally accepted in such a classification problem.

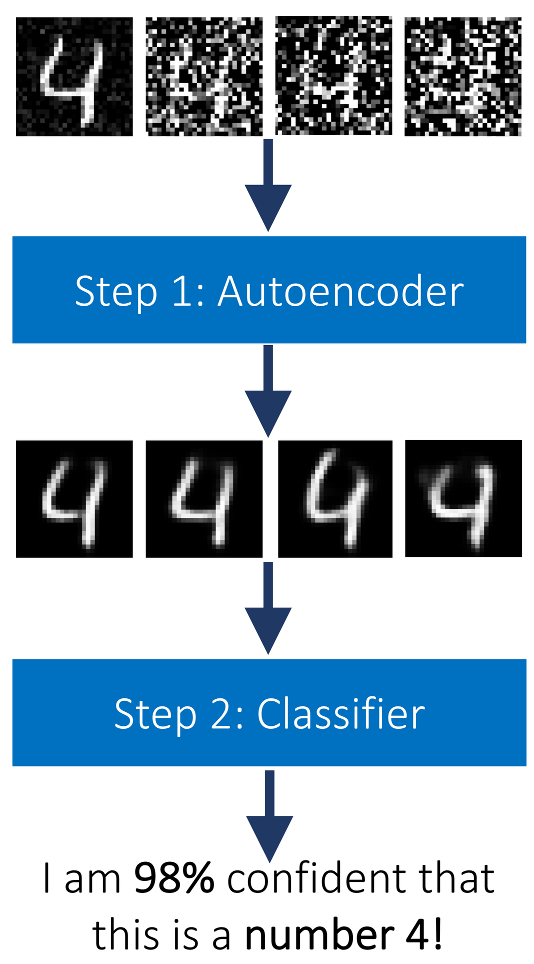

Figure 2: Process followed to train our two-step intelligent algorithms to find the optimal early stopping point.

Figure 3: Physical parameters in the experiment were varied, such as mask type (a) Walsh 2D and (b) Random and mask resolution (a - b) 48 x 48 pixels and (c) 96 x 96 pixels.

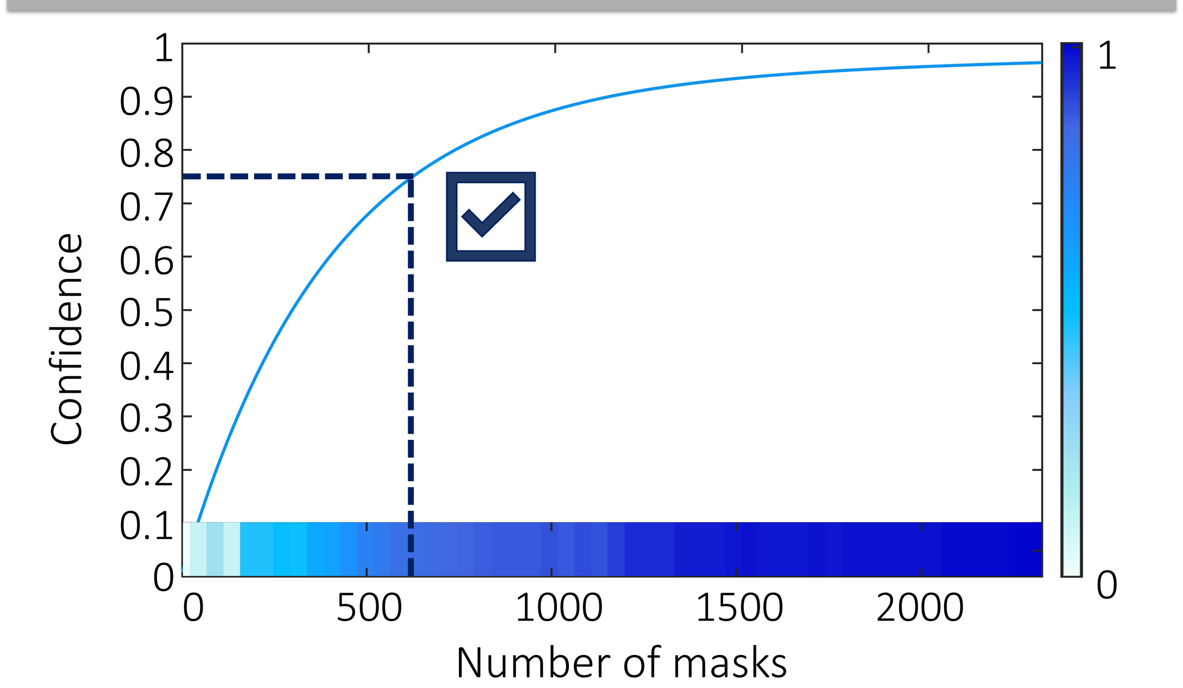

Figure 4: Confidence curve indicating optimal early stopping point. A compact confidence curve is shown at the bottom.

Results

We tested different objects (not shown), mask types and resolutions. Walsh 2D masks converge the quickest [3] and were therefore the focus of this study. In Fig. 5(a) the stopping point was achieved at ~45% while in the two-step approach (Fig. 5(b)) our stopping point is at an outstanding 22% of image acquisition time, successfully reducing image reconstruction time to less than a quarter of what was initially required. The two-step technique outperforms the recognition algorithm by more than 20%. Figure 6 shows that our technique is robust to different mask types and resolutions, successfully reducing acquisition time in all cases [4].

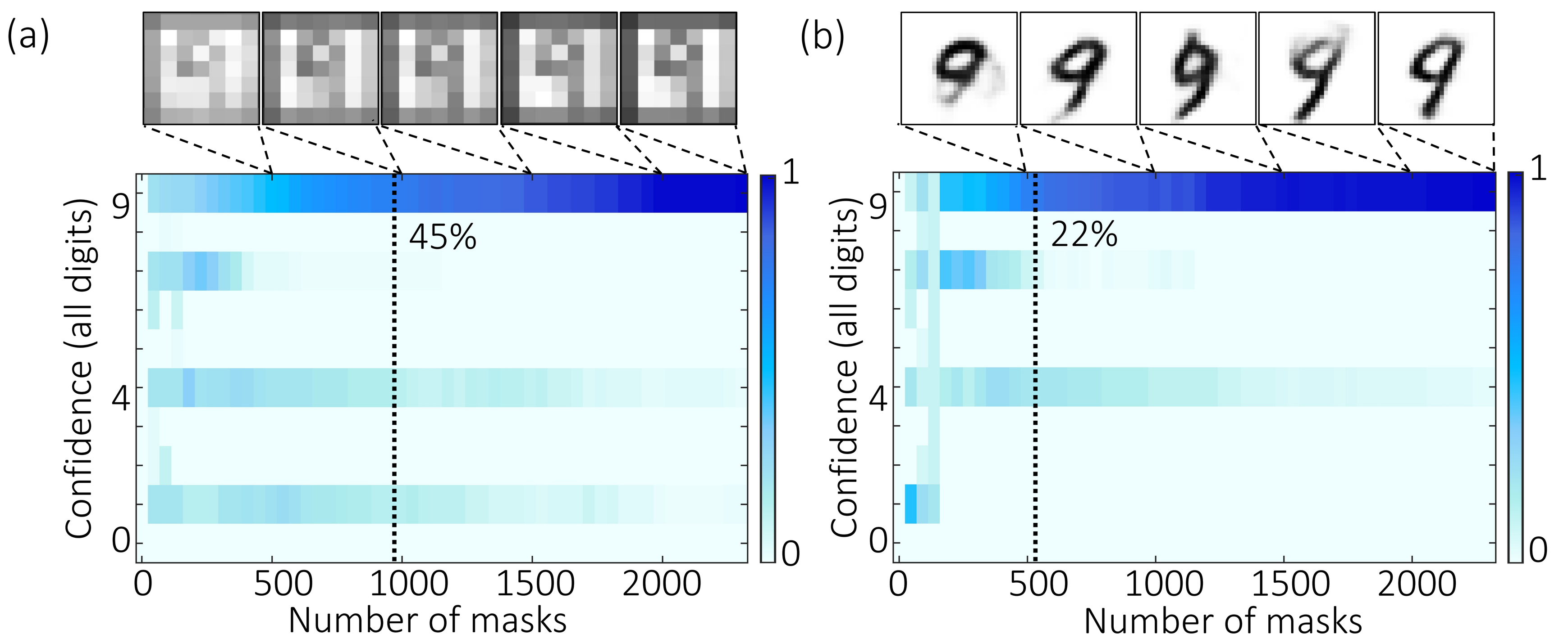

Figure 5: (a)Raw reconstructed images and (b) enhanced autoencoder images for object nine at 20 – 100% image reconstruction time in increments of 20%, respectively. Followed by the corresponding compact confidences curves for all digits for (a) a recognition algorithm alone and (b) our two-step approach. The vertical lines represent the point at which the stopping criteria was achieved. The object was reconstructed by 48 x 48 pixel Walsh 2D masks (2304 masks are initially needed to completely reconstruct the image).

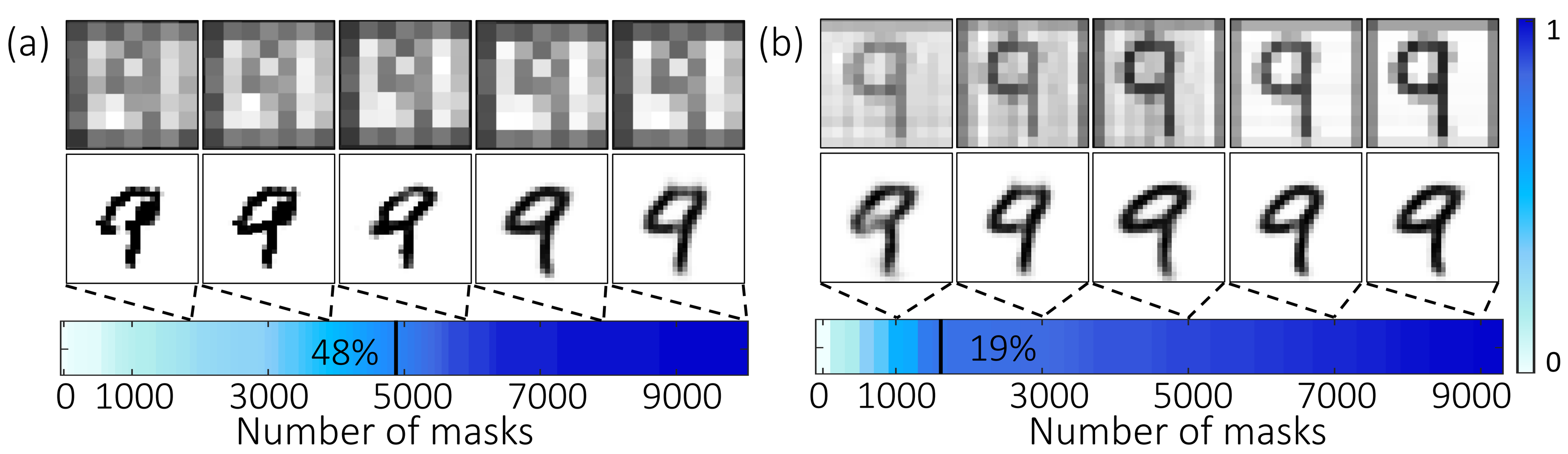

Figure 6: Raw reconstructed images, enhanced autoencoder images and compact confidence curves for (a) 48 x 48 pixel image from 10000 random masks and (b) 96 x 96 pixel image from 9216 Walsh 2D masks.

Summary

- We designed and implemented a two-step intelligent algorithm approach to establish an optimal early stopping point for ghost imaging experiments.
- We imposed a strict early stopping criteria of 75% confidence.
- Our novel two-step approach allows for reconstruction time to be reduced to 22%.
- Our technique is robust enough to handle different objects, mask types, mask resolutions and outperforms a one-step neural recognition algorithm.

References

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[3] V. Rodríguez-Fajardo, et. al. *"Towards time-efficient ghost imaging"*. Journal of Modern Optics (2020).
[4] C. S. Moodley, et. al., *"Deep learning early stopping for non-degenerate ghost imaging"*. Scientific Reports (2021).