

Hermite-Gaussian Mode Detection via Convolution Neural Networks

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Abstract—Hermite-Gaussian (HG) laser modes are a complete set of solutions to the free-space paraxial wave equation in Cartesian coordinates and represent a close approximation to physically-realizable laser cavity modes. Additionally, HG modes can be mode-multiplexed to significantly increase the information capacity of optical communication systems due to their orthogonality. Since, both cavity tuning and optical communication applications benefit from a machine vision determination of HG modes, convolution neural networks were implemented to detect the lowest twenty-one unique HG modes with an accuracy greater than 99%. As the effectiveness of a CNN is dependent on the diversity of its training data, extensive simulated and experimental datasets were created for training, validation and testing.

INTRODUCTION

Convolution neural networks (CNN) [?] have seen a resurgence in the last decade [?] due to their ability to classify images with near human or better than human accuracy [?]. These developments have revolutionized machine vision applications from cancer detection [?] to optics [?]. One area of optics research in which CNNs are proving useful [?] is laser beam profiling—where either a CCD or CMOS camera is used to determine the centroid, radius [?] and quality of a laser beam (M^2) among other metrics. Since, a laser beam's M^2 value is closely related to its modal content, determining the beam's dominant HG mode with a CNN is of significant interest. Furthermore, using CNNs to identify the HG [?] mode of a beam has applications ranging from optical communications to atomic physics.

Mode-multiplexing can significantly increase the information capacity of optical communication systems [?], [?] through use of Hermite-Gaussian (HG) and Laguerre-Gaussian (LG) modes whose respective constituent modes propagate independently of one another due to their orthogonality—HG as well as LG modes comprise a complete orthogonal basis set [?]. Much attention has been given to modes that carry orbital angular momentum (OAM); however, Zhao *et al.* suggested that OAM modes do not necessarily increase the information capacity of a system in comparison to non-OAM modes and furthermore, OAM modes are often more adversely affected by turbulence [?]. Although Trichili *et al.* showed that the full LG basis set of modes can encode information when multiplexing and demultiplexing data [?], HG modes propagate information in a free-space optical communication network with an equal information capacity [?] to LG modes and can experience lower mode loss and lower mode cross-talk [?], [?]. Since previous work has demonstrated the ability of deep neural networks to identify both OAM [?], [?], [?], [?] and LG modes [?], extending the use of CNNs to identify HG modes provides another route to mode-multiplexing with

potentially lower error rates.

Even though higher-order HG modes are useful in optical communications, they are problematic in optical setups that require only the fundamental TEM_{00} [?] mode. As an example, self-built external cavity diode lasers [?], often found in atomic physics labs, rely on a laser diode and diffraction grating which form an external cavity. The laser must be carefully tuned via temperature, current and grating position to produce the correct frequency and TEM_{00} spatial mode. Since the laser can mode-hop to oscillate in higher transverse (HG) modes [?], [?] during tuning, any automated tuning procedure would require a determination of the HG mode. This makes a machine vision HG mode characterization tool eminently useful.

In this paper, convolution neural networks (CNN) are used to accurately determine the Hermite-Gaussian mode of a laser beam. As CNNs require substantial amounts of labeled data, two separate datasets were created. First, a simulated dataset was generated for both training and validation of the CNN, whereas a second experimental dataset was created—using a spatial light modulator (SLM) and beam profiler—to test the CNN's ability to generalize to new data and adapt to experimental conditions. The mathematical form of HG modes is first described, followed by the simulated dataset, the SLM optical setup and the experimental dataset. Finally, the CNNs are detailed along with the training methods used to achieve the best classification of the HG modes.

In contrast to other state-of-the-art-mode detection techniques [?], which utilize computer generated holograms in all-optical setups [?], the method developed requires little to no optics and is additionally devoid of physically imposed constraints which limit the number of modes other methods can detect (e.g. the number of modes a single hologram can successfully demultiplex). Although single image evaluation times can be longer for the CNN mode detection method in comparison to all-optical techniques [?], recent advances in both CNN software architecture and processing chips designed for deep learning [?] should substantially

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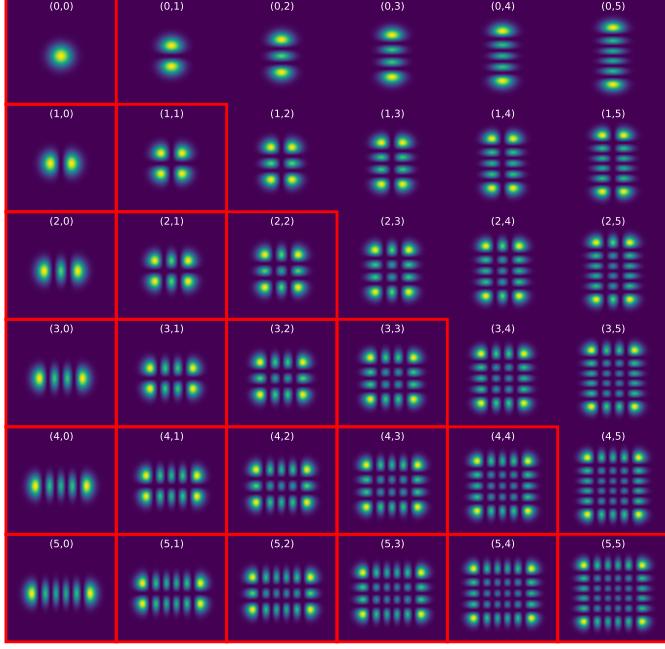


Fig. 1. Intensity distributions of the lowest 36 Hermite-Gaussian modes. When considering rotational transformations, only 21 unique modes (bordered subplots) remain.

lower evaluation times in the future.

HERMITE-GAUSSIAN MODES

The HG modes represent a set of solutions to the free-space paraxial wave equation in Cartesian coordinates [?]. Along one dimension a HG mode's electric field is

$$u_n(x, z) = \left(\frac{2}{\pi}\right)^{\frac{1}{4}} \left(\frac{e^{-i(2n+1)\psi(z)}}{2^n n! w(z)}\right)^{\frac{1}{2}} H_n\left(\frac{\sqrt{2}x}{w(z)}\right) e^{-i\frac{kx^2}{2R(z)} - \frac{x^2}{w^2(z)}} \quad (1)$$

where n is the mode of the higher-order beam, k is the wave vector and H_n is a Hermite polynomial of order n . The radius of the beam $w(z)$ at a given location z along the axis of propagation is

$$w(z) = w_0 \left[1 + (z/z_R)^2\right]^{\frac{1}{2}} \quad (2)$$

where w_0 is the radius of the beam at the beam waist and the Rayleigh length is defined as $z_R = \pi w_0^2 / \lambda$ —with the wavelength of the beam denoted by λ . The Gouy phase is given by $\psi(z) = \tan^{-1}(z/z_R)$ and lastly, the radius of curvature is $R(z) = z \left[1 + (z_R/z)^2\right]$.

The HG mode's two-dimensional electric field is given by

$$u_{nm}(x, y, z) = u_n(x, z) u_m(y, z) \quad (3)$$

where $u_m(y, z)$ has a similar form to Eq. ???. The intensity distribution of the HG mode (see Fig. ???) can be determined [?] via

$$I(x, y, z) = u_{nm}(x, y, z) u_{nm}^*(x, y, z) \quad (4)$$

and the phase distribution $\phi(x, y, z)$ is calculated by taking the angle of $u_{nm}(x, y, z)$ in the complex plane.

SIMULATED DATA

Convolution neural networks require significant amounts of labeled data to properly train and thus a simulated dataset was generated using Eq. ???. A Python program was written to generate arbitrary HG mode electric field distributions from which their respective intensity and phase distributions were obtained. Since the accuracy of the CNN and its ability to generalize to new data increases with the diversity of its training set, the simulated data was generated to cover a parameter space consisting of the beam's radii along the major and minor axes (w_{0x}, w_{0y}), the beam's centroid (x_0, y_0) and the orientation of the beam θ . The beam's amplitude was not included in the parameter space since the resulting image is normalized before passing into the CNN. Furthermore, the beams were simulated at the beam waist since the beam's position along the axis of propagation does not generate unique data. Rather than mapping the beam parameter space, each of the parameters was randomized within physically realizable bounds.

First, the bounds for the beam radii were determined. To resolve an HG mode along one axis, a dark pixel should be seen on either side of each HG lobe thus requiring a minimum of $(2n + 3)$ pixels—with the assumption that the lobe spacing is quasi-sinusoidal. This in turn results in a minimum input radius of

$$w_{0\min} = \sqrt{2} p_w (2n + 3) \quad (5)$$

where $\sqrt{2} p_w$ is the maximum distance (at a beam orientation of $\theta = \pi/4$) across a square pixel with width p_w . The maximum beam radius along both the major and minor axes is given by $w_{\max} = s_l/3$, where s_l is the simulated sensor size; larger radii would cause significant portions of the beam's power to be located off the simulated sensor. However, the HG beam radius increases with the mode order n even though the input radius w_0 remains constant (see Fig. ??a) [?]. Therefore, a scaling factor β is numerically determined for each HG mode (see Fig. ??b) and multiplied with the desired output radius to give the correct input radius. Thus, the maximum input radius is

$$w_{0\max}(n) = \frac{1}{3} s_l \beta(n). \quad (6)$$

Using $w_{0\min}$ and $w_{0\max}(n)$ a random radius can be generated for both the major and minor axes after which a random orientation for the beam is chosen with $0 \leq \theta \leq 2\pi$.

After choosing the beam radii and orientation, valid bounds for the centroid are found such that the beam does not exceed the dimensions of the simulated sensor. Since the centroid values are given with respect to the image axes rather than the beam's major and minor axes, the beam radii along the image axes are calculated as follows

$$w_x = \pm \sqrt{w_{0x}^2 \cos^2 \theta + w_{0y}^2 \sin^2 \theta} \quad (7)$$

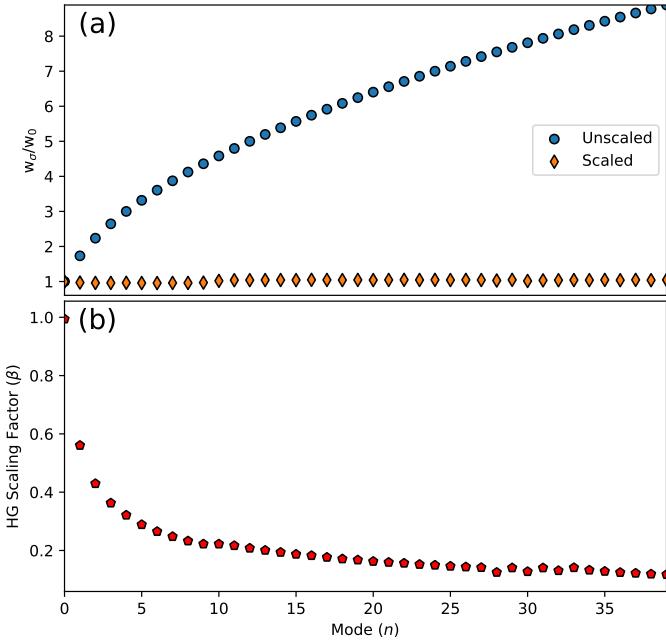


Fig. 2. (a) Ratio of the measured Hermite-Gaussian (HG) beam radius w_σ and its respective input beam radius w_0 (see Eq. ??) as a function of the HG mode n along a single axis. Both input radii with the HG scaling factor (diamonds) and without the scaling factor (circles) are shown. (b) The HG radius scaling factor β as a function of the mode n .

$$w_y = \pm \sqrt{w_{0x}^2 \sin^2 \theta + w_{0y}^2 \cos^2 \theta} \quad (8)$$

and the bounds for x_0 are then given by

$$x_{0\text{bounds}} = \pm (s_l/2 - \alpha w_x) \quad (9)$$

with a similar equation for the y_0 bounds except that w_x is replaced by w_y . Due to the HG modes extending towards infinity, the radius is scaled by $\alpha = 1.5$ such that a majority of the beam's power is incident on the simulated sensor. Using the centroid bounds, random values for the centroid are generated.

After generating a randomized beam, the maximum amplitude is scaled to one and Gaussian noise added to simulate experimental conditions. The standard deviation of the noise is itself randomly pulled from a Gaussian distribution which has a standard deviation of $\sigma = 0.02$ and replicates real noise values seen on a sensor. After the noise has been added, the images are saved as PNGs (224×224 pixels) which both compresses and scales the data between 0 and unity. A training dataset and a validation dataset (see Fig. ??) are generated with 300 and 200 images respectively for each of the lowest twenty-one unique HG modes (see Fig. ??).

EXPERIMENTAL DATA

To further validate the CNNs' effectiveness, an optical setup was constructed to create HG beams and acquire their images (see Fig. ??). A single mode fiber-coupled laser with a 675 nm wavelength and an initial diameter of 1 mm was used as the source and passed first through a polarizer,

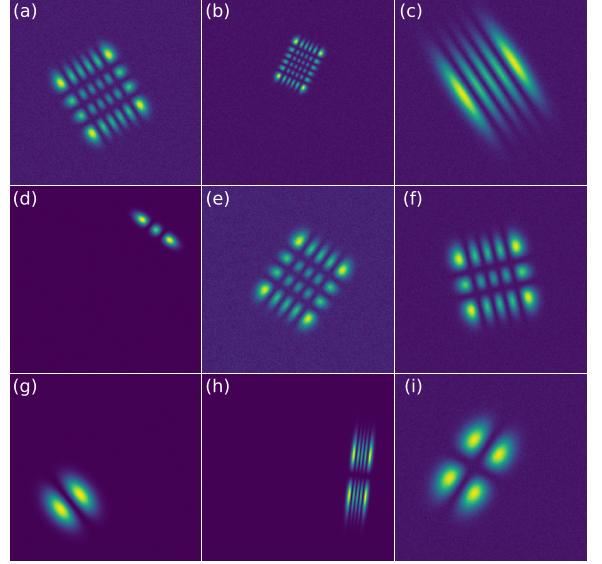


Fig. 3. Subset of the simulated beams used to train and validate the convolution neural network. The simulated beams are given random values for the beam radii, beam centroid and orientation of the beam. Additionally, Gaussian noise is added to each image to approximate real-world conditions.

which ensured the beam was linearly polarized along a single axis, followed by a lambda half-waveplate. The beam was then expanded to 9 mm in diameter and was incident on a spatial light modulator (SLM) at a slight angle with the preceding half-waveplate used to orient the beam's polarization parallel to the SLM's vertical axis. Computer generated holograms (CGH) with blazed gratings were loaded onto the SLM to create the HG modes. Following the SLM, the beam passed through a 400 mm aspheric focusing lens which separated the different diffraction orders—arising due to the CGH's blazed grating—near the focus and an aperture then allowed only the first-order beam to be imaged by the beam profiling camera.

The optical setup centered on the spatial light modulator which enabled the phase of the electric field to be modulated on a per-pixel basis through the use of nematic liquid crystals [?]. A Meadowlark Optics SLM was used with a resolution of 1920×1152 , square pixels of width $9.2 \mu\text{m}$ and a fill factor of 95.7%. Although phase-only modulation holograms can be used to create higher-order modes [?], Arrizon *et al.* demonstrated that both the phase and amplitude of the outgoing beam can be modulated with a phase-only SLM [?] through the use of complex amplitude modulation (CAM) holograms (see Fig. ??c-d).

CAM holograms produce better quality HG modes than phase-only holograms [?] and were utilized to generate the experimental dataset (see Fig. ??a-b). The HG amplitude and phase distributions were calculated through Eq. ?? and then used in the CAM hologram. Similar to the simulation dataset, the beam parameters of the holograms, including the beam radii and the orientation of the beam, were randomized to increase the diversity of the experimental dataset. Because the quality of the output HG beam deteriorated when the SLM's input beam was not centered on the hologram's centroid, the centroid position was kept

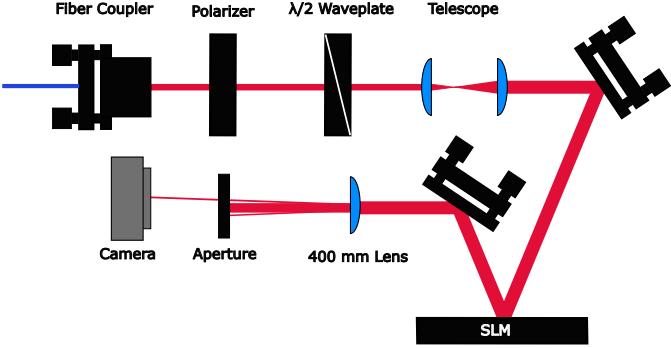


Fig. 4. Optical setup for generating arbitrary Hermite-Gaussian beams. A 675 nm fiber-coupled laser beam exits the fiber-coupler and immediately passes through a polarizer followed by a $\lambda/2$ half-waveplate (HWP) both in rotation mounts. The beam is expanded through a series of lenses and is then incident on the SLM. The HWP preceding the SLM is rotated to align the beam polarization parallel with the vertical axis of the SLM. A complex-amplitude modulation hologram is applied to the SLM and the reflected beam then passes through a 400 mm lens which allows the various diffraction orders—due to the hologram's blazed grating—to be separated at the lens' focus. Finally, the first-order diffracted beam is separated via an aperture and imaged with a beam profiling camera.

constant.

The CAM holograms [?] contained a blazed grating which created various diffraction orders clearly seen at the focal plane of the lens following the SLM. The aperture near the focal plane isolated the first diffraction order—which contained the best representation of the HG beam—and an image was subsequently acquired by a beam profiling camera placed in the lens' Fourier-plane. During acquisition of the experimental dataset, the camera's software automatically adjusted the image exposure and between 115–120 randomized images with dimensions of 256×256 pixels were recorded for each of the twenty-one HG modes.

CONVOLUTION NEURAL NETWORK

In keeping with the simulation and data acquisition programs, a Pythonic approach to implementing the CNNs was taken with PyTorch's [?] deep learning framework. PyTorch has popular CNNs pretrained on the ImageNet dataset [?], which allowed transfer learning [?] to be taken advantage of and significantly shortened the training time required for a CNN. Although several successful CNN architectures have been put forth in recent years including AlexNet [?], VGG [?] and ResNet [?] among others [?], [?] ResNet was chosen, as it achieves more accurate results on the ImageNet dataset compared to older CNNs such as AlexNet. Additionally, ResNet has several million fewer parameters than a VGG CNN with comparable depth which decreases the training time and, when deployed, the evaluation time per image. However, ResNet itself has several implementations differing primarily with regards to the depth of the neural network and 18, 34, 50, 101, and 152 layer pretrained variants are available with PyTorch. Generally, a deeper neural network can achieve higher accuracies; however, deeper networks also have far more parameters and thus require longer training times, take more system memory, and increase single image evaluation times. Therefore, we

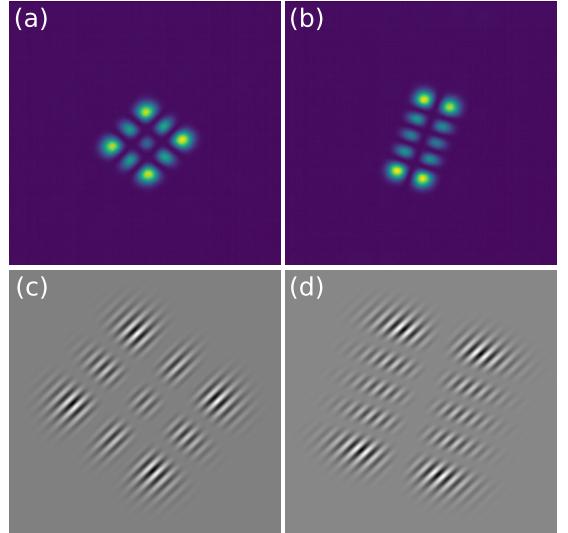


Fig. 5. (a)-(b) Sample of the experimental dataset images used in testing the convolution neural networks with each image consisting of 256×256 pixels. (c)-(d) The complex amplitude modulation (CAM) hologram used to generate the corresponding intensity distribution above. Note, the blazed grating frequency in each CAM hologram has been decreased by 80% to increase its visibility.

opted to work with the smaller ResNet versions: ResNet18 and ResNet34. Furthermore, the CNNs were trained in the cloud with Google Compute Engine's Deep Learning virtual machine utilizing a Tesla P100 NVIDIA GPU.

After choosing the ResNet models, several parameters were set to achieve maximum accuracy on the simulated and experimental data sets. Cross entropy loss was utilized as the loss function for every CNN trained, whereas both Adam [?] (an adaptive optimizer) and stochastic gradient descent (SGD) were used for the optimizer function. However, after initial testing, we found, in keeping with recent literature [?], that SGD was better able to generalize and achieved higher accuracy results on the experimental dataset than Adam. Thus, the following CNNs were trained using SGD with momentum as the optimizer.

Lastly, data transforms were used throughout both the training and validation steps. Since increasing the diversity of the CNN's training data increases the CNN's ability to generalize to new data, two transforms were used during training. In the first transform, the images were randomly cropped between 0.08 and 1.0 of the initial image size after which they were given a random aspect ratio between 3/4 and 4/3 and finally resized to 224×224 pixels. The second transform randomly flipped 50% of the images along the horizontal axis before normalizing them and passing them into the CNN. During validation, the input data was not substantially altered; rather, the images were cropped to 224×224 pixels about the center of the image to match the CNN's expected input size and then normalized before entering the CNN.

The image resolution of 224×224 pixel was chosen to match the input layer of the pre-trained ResNet CNNs. Although higher resolution images can increase a CNN's classification accuracy [?], they simultaneously increase both

Model	Learning Rate	Best Exp. Acc. (%)	Best Corr. Acc. (%)	Time (m)
ResNet18	0.1	31.19	66.10	43.1
ResNet18	0.01	56.46	91.07	39.8
ResNet18	0.001	99.56	99.31	39.5
ResNet18	0.0001	90.74	98.31	39.7
ResNet34	0.1	37.70	65.88	56.7
ResNet34	0.01	29.56	96.74	50.4
ResNet34	0.001	98.57	97.43	50.3
ResNet34	0.0001	98.45	99.29	50.3

TABLE 1

The initial results of the convolution neural networks with fixed learning rates are shown. Each CNN has a batch size of eight and a momentum of $\mu=0.9$. A model's best accuracy on the experimental dataset along with the corresponding accuracy on the simulated dataset is given in addition to the total time (minutes) to train the model for forty epochs. Note that the highest accuracy ResNet18 and ResNet34 CNNs display oscillatory behavior around the asymptote (see Fig. ??a-b).

training and single image evaluation times. Therefore, to mitigate potentially detrimental effects on the classification accuracy due to the image resolution, both the simulated and experimental datasets were constructed such that the dominant features (lobes) of the modes were always resolvable.

RESULTS

Once the loss and optimizer functions along with the data transforms were determined, the CNNs hyperparameters including the batch size (in this case, the number of images fed into the CNN at a time), learning rate and momentum were tuned. Initially, the CNNs were trained for forty epochs (number of times the entire dataset is passed through the CNN) with a batch size of eight, a momentum of $\mu = 0.9$ and constant learning rates of $\{0.1, 0.01, 0.001, 0.0001\}$ (see Table ??). A constant learning rate of 0.001 was optimal for ResNet18 and a maximal accuracy of 99.56% was achieved on the experimental dataset, with a corresponding accuracy of 99.31% on the simulation dataset (see Fig. ??a). For ResNet34 a constant learning rate of 0.0001 proved best (see Fig. ??b) yielding a maximum accuracy of 98.45% on the experimental dataset and a coinciding accuracy of 99.29% on the simulation dataset. ResNet18 alone was subsequently used as it achieved similar accuracy to ResNet34 and its smaller size decreased training and evaluation times. After training, the ResNet18 evaluated images in approximately 100 milliseconds on a CPU and 5 milliseconds when utilizing the GPU.

Although the CNNs achieved fairly high results on both the simulated and experimental datasets, their accuracies on the experimental dataset failed to reach satisfactory asymptotes but rather oscillated substantially from epoch to epoch—indicating the hyperparameters were not properly tuned to target a local minimum. This is problematic if the training dataset is altered slightly. As an example, a second random simulated dataset was generated (utilizing the same bounds as the first), and used to train a set of

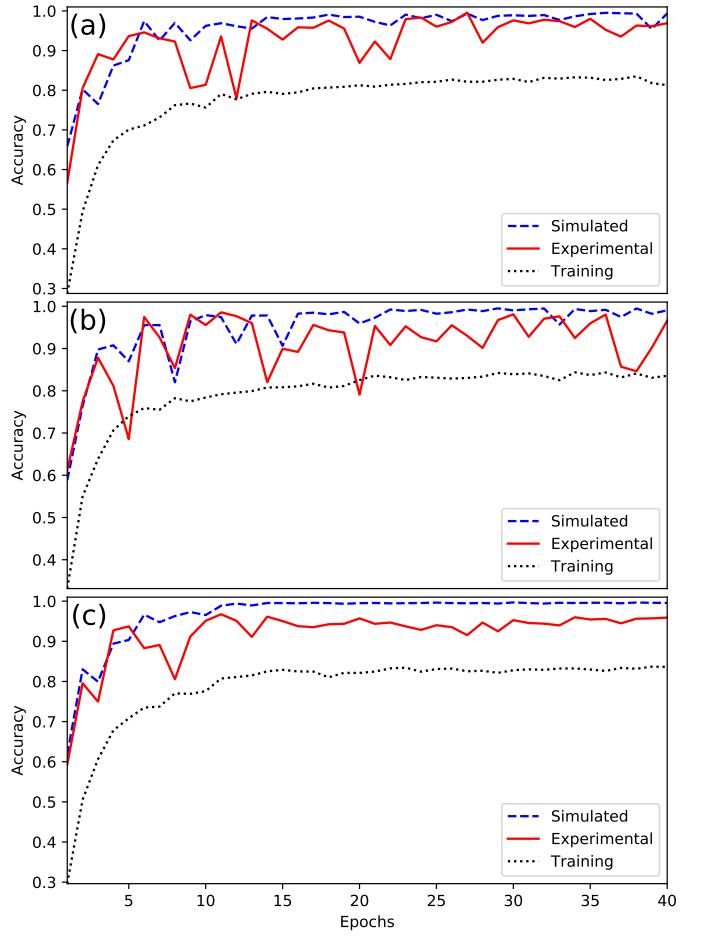


Fig. 6. (a) Accuracy of a ResNet18 convolution neural network (CNN) as a function of the epoch with a constant learning rate of 0.001, momentum of $\mu=0.9$ and batch size of eight. The best accuracy achieved on the experimental dataset was 99.56%. (b) Accuracy of a ResNet34 CNN as a function of the epoch for a constant learning rate of 0.0001. The momentum and batch size were the same as in (a), whereas the highest accuracy attained on the experimental dataset was 98.45%. (c) Accuracy of the ResNet18 CNN as a function of the epoch with a batch size of eight and momentum of $\mu=0.9$. The learning rate was initially set to 0.001 and reduced by an order of magnitude every ten epochs. Although the maximum experimental accuracy (96.74%) was reduced, it oscillated far less than (a) or (b) and was fairly asymptotic.

CNNs with same hyperparameters as above. In this case, the best accuracy achieved for a ResNet18 CNN (learning rate of 0.001) dropped to 98.05% and 99.31% on the experimental and simulated datasets respectively.

To better target a local minimum during training, a step scheduler was employed in which the learning rate was decreased by an order of magnitude every ten epochs. This was tested for a series of CNNs with batch size eight, momentum of $\mu=0.9$ and initial learning rates of $\{0.1, 0.01, 0.001, 0.0001\}$. The best performing CNN (see Fig. ??c) had an initial learning rate of 0.001 and resulted in an accuracy of 96.74% on the experimental dataset and 98.86% on the simulation dataset. Even though the best ResNet18 CNN trained with a fixed learning rate had higher accuracies, the CNN trained with the step scheduler showed substantially lower amplitude oscillations around the asymptote demonstrating a local minimum was more effectively reached.

Learning Rate	Momentum	Batch Size	Best Exp. Acc. (%)	Corr. Acc. (%)
0.014367	0.864872	64	99.44	99.57
0.025743	0.357709	16	99.21	99.55
0.069024	0.135448	64	98.81	99.55
0.014746	0.283051	16	98.77	99.17
0.035026	0.776323	32	98.53	98.90

TABLE 2

Results from the optimized ResNet18 convolution neural networks which utilized a hyperparameter random search in conjunction with a step scheduler. The initial learning rate was randomized between 0.1 and 0.001, the momentum was bounded by 0 and 1 and the batch size was set to 2^l , where l was an integer given by $3 \leq l \leq 8$. The best accuracy on the experimental dataset along with the corresponding accuracy on the simulation dataset is given for each model (see Fig. ??a for accuracy vs. epoch).

In an effort to achieve both the high accuracy of the fixed learning rate run and the asymptotic behavior of the scheduled run, a random search [?] of the hyperparameters was employed in conjunction with the step scheduler. The scheduler decreased the learning rate by a factor of ten every seven epochs and bounds were set for each hyperparameter with an initial learning rate between 0.1 and 0.001, a momentum of $0 \leq \mu \leq 1$ and a batch size of 2^l where l is an integer given by $3 \leq l \leq 8$. Fifty different sets of hyperparameters were randomly chosen from within these bounds and then trained for thirty epochs each (see Table ??). The CNN with the highest accuracy (learning rate 0.0143673, momentum $\mu = 0.864872$, batch size of 64) on the experimental data attained an accuracy of 99.44% and a corresponding accuracy of 99.57% on the simulated dataset (see Fig. ??a). Thus, the overall accuracy was slightly higher than for the CNN trained with a fixed learning rate; however, just as importantly, the accuracy on both the simulation and experimental datasets become asymptotic indicating a local minimum was satisfactorily reached.

Finally, the highest accuracy CNN from the random search was utilized without pretraining to determine the effect of transfer learning. The ResNet18 CNN was trained for sixty epochs with an initial learning rate of 0.0143673, momentum of $\mu=0.864872$ and batch size of 64 (see Fig. ??b). The CNN obtained a maximum accuracy of 31.31% on the experimental dataset and a corresponding accuracy of 92.40% on the simulation dataset—which was substantially lower than pretrained model’s accuracies for both datasets. Furthermore, the relative accuracy difference between the non-pretrained CNN and the pretrained CNN was significantly larger on the experimental dataset than the simulation dataset. This indicates that pretraining increased the overall accuracy of the CNN and additionally had an outsized impact on the CNN’s ability to generalize to real world data.

CONCLUSION

We have demonstrated that a convolution neural network (CNN) can be used to classify the lowest twenty-one unique Hermite-Gaussian (HG) modes with an accuracy of 99.44%.

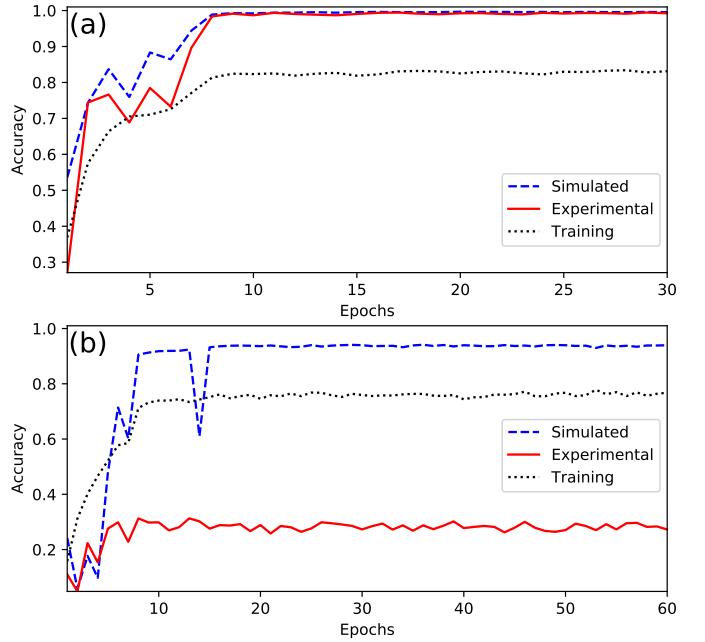


Fig. 7. (a) Accuracy of a ResNet18 CNN as a function of the epoch with a batch size of 64 and momentum of $\mu=0.864872$. The learning rate was initially set to 0.0143673 and reduced by an order of magnitude every seven epochs. Note that the overall accuracy achieved—99.44% on the experimental dataset, 99.57% on the simulated dataset—was slightly better than the CNN trained with the fixed learning rate (see Fig. ??a) and furthermore displayed minimal oscillations around the asymptote indicating a local minimum was more effectively reached. (b) Accuracy of a ResNet18 CNN as a function of the epoch with the same hyperparameters as (a), but without pretraining on ImageNet. The best accuracy achieved was 31.31% on the experimental dataset corresponding to 92.40% on the simulation dataset; thus, pretraining in (a) significantly increased the CNN’s accuracy in comparison to the non-pretrained CNN in (b).

The primary CNN used was an eighteen layer ResNet variant trained with a step scheduler for the learning rate and hyperparameters tuned with a random search. To facilitate in training the CNN, a large simulated dataset of HG modes was created in which each of the beam’s parameters including orientation, centroid and radii were randomized within physically realizable bounds. Furthermore, an experimental dataset of HG modes was acquired through an optical setup utilizing a spatial light modulator and was used to test the CNN’s ability to generalize to real-world data and experimental conditions.

As stated previously, the trained CNN could be used to automatically tune the transverse HG mode output of a laser cavity or detect HG modes in optical communications. Since the current training dataset contains unique modes in random orientations, a beam under evaluation can be determined irrespective of orientation which is particularly useful in a laboratory setting. If the application of the CNN were solely optical communications, a dataset could also be constructed using all the modes (not only the unique ones); however, this would require a further bound on the orientation of the beams in the simulated dataset and additionally the beam would need to be correctly oriented with respect to the camera when the CNN is deployed.

In the future, a larger data set of modes could be both

simulated and experimentally acquired. Moreover, superpositions of various HG modes could also be labeled as individual classes for input into the CNN. This would allow the data in a multiplexed beam to be determined without explicitly demultiplexing the beam with optics. However, this is bounded by the finite number of classes a CNN can accurately classify—which is problematic as the number of classes grows exponentially with the modes in the multiplexed beam.

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