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Classifying the gravitational waves using the deep learning technique

Abstract

Gravitational waves are related to the concept of vibration of space-time curvature. When the body of heavy masses lies on the four-dimensional space-time and changes their position with turbulence motion then actually they create a disturbance in the space. The disturbance travels outward from the origin having light velocity is known as gravitational waves. Laser Interferometer Gravitational-Wave Observatory (LIGO) scientific teamwork declared the identification of these waves. In this paper, we review Gravitational waves, Detection of gravitational waves, deep learning for the classification of gravitational waves. We design and develop a deep learning system to classification gravitational waves of the dataset 'Gravity Spy (Gravitational waves)' that is made up of the LIGO images. The goals of this research are to gain a piece of reasonable and useful knowledge about Gravitational waves and propose an effective deep learning network system to classify the gravitational waves. The accuracy achieved by our model is 99.34%.

Keywords: Gravitational wave, LIGO image, Deep learning, Neural Network

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Introduction

The gravitational waves[1] are related to the concept of vibration of space-time curvature. When the body of heavy masses lies on the four-dimensional space-time and changes their position with turbulence motion then actually they create a disturbance in the space. The disturbance travels outward from the origin having light velocity is known as gravitational waves. Gravitational waves, coming from a body and moving with the velocity of light, as being required by the non-Galilean transformations which was first mentioned in 1905 by Henri Poincare,[2] and later on, he explained the similarities between an accelerating electrical charge conducting electromagnetic waves and gravitational waves as an accelerated mass in the gravitational field. Our earth lies in space, so when the gravitational wave passes through the earth then the earth is once contracted and once stretched, and which value is 10^(-21) units. The quadruple wave is very weak.

Laser Interferometer Gravitational-Wave Observatory (LIGO)[3] scientific team-work declared on the date of February 11, 2016, the identification of these waves, from a signal identified at 09:50:45 GMT, and on September 14, 2015, of the binary system of rotating black holes having 29 and 36 times of solar masses combining simultaneously around 1.3 billion light-years away. This wave uses space as a medium because of being a quadruple wave. Deep learning[4] is a part of machine learning based on the Artificial Neural Network (ANN) and used for representation learning. At present time several types of architectures are used for deep learning, such as - deep neural network (DNN), deep belief network (DBN), recurrent neural network (RNN), convolution neural network (CNN), etc. Those architectures are commonly applied for several fields, such as - image classification, computer vision, speech recognition, audio recognition, natural language processing (NLP), machine translation, social network filtering, bioinformatics, medical image analysis, etc.

The convolution neural network (CNN)[5] is the most commonly used deep learning network to analyze visual imageries. The CNNs perform a mathematical operation on image data known as convolution. In section-II of this paper, we review Gravitational waves, Detection of gravitational waves, deep learning for the classification of gravitational waves. We also briefly describe the history of gravitational waves. In section-III of this paper, we design and develop a deep learning system to classification gravitational waves of the dataset 'Gravity Spy (Gravitational waves)'[6] that is made up of the LIGO images. To classify the Gravitational waves, we use a deep learning network model with ten layers. In section-IV of this paper, we represent the result we achieved using our deep learning model. The goals of this research are to gain a piece of reasonable and useful knowledge about Gravitational waves and propose an effective deep learning network system to classify the gravitational waves.

Review

A. Gravitational waves

Gravitational waves are related to the concept of vibration of space-time curvature. When the body of heavy masses lies on the four-dimensional space-time and changes their position with turbulence motion then actually they create a disturbance in the space. The disturbance travels outward from the origin having light velocity is known as gravitational waves. The gravitational wave is not conventional Transverse or longitudinal waves. This wave goes ahead by contracting and speeding the space-time vertically and horizontally which is nothing but quadruple type. Gravitational waves are nothing but the ripples in the curvature of space-time which stretch as waves, moving outward from the source. It carries energy as gravitational radiation. These types of radiation are created by accelerating masses as like the accelerating charges create electromagnetic radiation.

In 1687, Sir Isaac Newton[7] introduced his most popular "law of universal gravitation", he described with his equation the gravitational attraction created between two objects. The gravitational attraction operated across space. In 1893, Oliver Heaviside[8] explained the possibility of gravitation using the similarity between the electricity and inverse-square law in gravitation. Gravitational waves, coming from a body and moving with the velocity of light, as being required by the non-Galilean transformations which was first mentioned in 1905 by Henri Poincare[9], and later on, he explained the similarities between an accelerating electrical charge conducting electromagnetic waves and gravitational waves as an accelerated mass in the gravitational field.

From 1907 to 1915, Albert Einstein[10] developed the theory of General relativity. The theory of general relativity states that the observed effect of gravitational between masses results from the warping of space-time.

In 1915, Albert Einstein doubted Henri Poincare's idea as gravitational dipoles were absent in his theory and Einstein himself took the various approximations to explain it. But the results of Einstein's approximations carried many suspicions. Nevertheless, Einstein's types of waves were great citations of the coordinate system which was shown in 1922 by Arthur Eddington.[11]

In 1936, Nathan Rosen and Albert Einstein[12] made a little bid that gravitational waves could not exist in general relativity as a singularity would exist in the solution of the field equations.

In 1956, Felix Arnold Edward Pirani[13] published a classic article for further development of the Theory of Relativity.

In 1957 the first "GR" conference at Chapel Hill, Richard Feynman[14] proposed that gravitational waves carry the energy.

In Einstein's theory of general relativity, gravity is a geometrical manifestation of space-time curvature. The masses create this curvature.

The curvature changes to reflect the changed location of that mass due to the mass moving around in space-time (Figure 1).

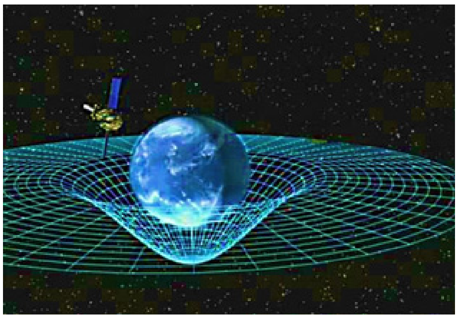

Figure 1 Illustration of mass bends space [Credit: NASA].

In certain situations, accelerating objects produce changes in this curvature, which propagate outwards at the speed of light in a wavelike manner. These propagating phenomena are known as gravitational waves. Gravitational waves go through regions of space that electromagnetic waves cannot.

Detection of gravitational waves

Our earth lies in space, so when the gravitational wave (Figure 2) passes through the earth then the earth is once contracted and once stretched, and which value is 10^{-21} units. The quadruple wave is very weak. Gravitational waves may subsist at any vibration and incredibly identifiable limit between 10^{-7} to 10^{11} Hz. It would not be possible to detect low-frequency waves, whereas there is no feasible origin for identifiable waves of very high frequency powerful and dynamic origins of identifiable gravitational waves comprise binary star method made of neutron stars, white dwarfs, and black holes.

"Weber Bars" the first gravitational wave detectors (Figure 3) were designed and built by Joseph Weber[15] after the Chapel Hill conference and in 1969 he claimed to detect the first gravitational waves but by the mid-1970s Weber bars across the globe failed to find out any signals although Weber's results were spurious.

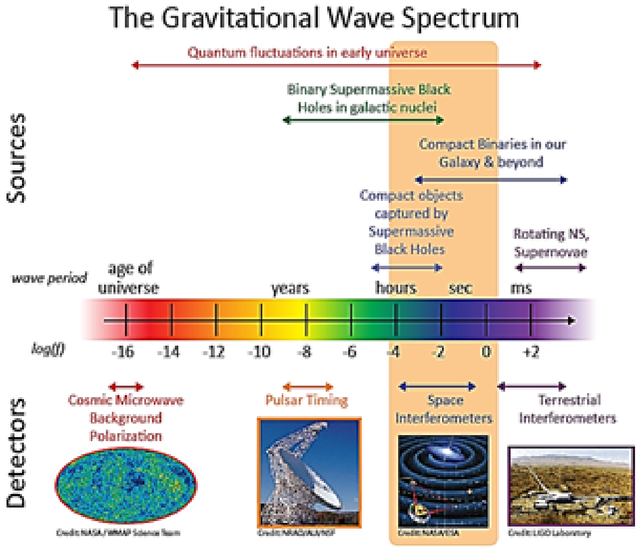

Figure 2 Gravitational wave spectrum [Credit: NASA].

Figure 3 Joseph Weber and one of his gravitational wave detectors.[16]

The first "Binary Pulsar" was revealed by two great physicists Russell Alan Hulse and Joseph Hooton Taylor Jr. in 1974[17] which were observed over the next decade. Due to ineffective outcomes, in 2015 all of the detectors became operational. Eventually, a great announcement of the first observation of gravitational waves was given by the LIGO and VIRGO collaborations. In 2017 Rainer Weiss, Kip Thorne, and Barry Barish[18] were given the Nobel Prize for the discovery of these waves.

Laser Interferometer Gravitational-Wave Observatory (LIGO) scientific team-work declared on the date of February 11, 2016 the identification of these waves, from a signal identified at 09:50:45 GMT on September 14, 2015 of the binary system of rotating black holes having 29 and 36 times of solar masses combining simultaneously around 1.3 billion light-years away. This wave uses space as a medium because of being a quadruple wave. By the propagation and contraction of the medium, this wave spreads out through space. At the time of ultimate trifling of a second of uniting, it released more power than 50 times that of all the stars in the apparent creation. The individual sweeps upwards in the range of frequency between 35 and 250 Hz.

Two units of energy (one unit is equivalent to 62 solar masses and another is equivalent to 3 solar masses) obtained from two rotating black holes emitted as gravitational waves. In Livingston and Hanford, with a time difference of 7 milliseconds due to the angle between the two identifiers and the source, the detectors of LIGO detected the signal. Due to unsmooth instruction of Magellanic winds the signal came from the Southern Celestial Hemisphere. Two vital and individual characters exist in Gravitational waves. Between these two the first is no necessity for any kind of body to appear close to for the creation of the waves by two rotating but uncharged black holes in which electromagnetic radiation cannot emit. The 2nd is, without being scattered significantly the gravitational waves can pass through any interior matter. Light from remote stars may be obstructed out by intersidereal dust, while gravitational waves will pass through basically unrestricted. There we can say gravitational waves carry information about astronomical phenomena never before observed by humans.

Virgo the International scientific collaboration was formed in 1993 which is situated at Santo Stefano a Macerata, Cascina in Italy. The Headquarters of this institute is in European Gravitational Observatory. The purpose of Virgo is to detect the Gravitational-wave. With 520 members of 99 institutes in 11 countries, the Virgo Collaboration was formed. The French institute CNRS and the Italian institute INFN authorized the Virgo project in 1993 and 1994 respectively. In 1996, the working of the detector originated in Cascina, Italy. EGO consortium the European Gravitational Observatory was created by the two institutes INFN and CNRS in 2000. The Virgo detector was created and completed in June 2003. By December 2015, EGO was a member of the Virgo collaboration. To detect gravitational waves the Virgo interferometer is a large interferometer which is a Michelson interferometer that is diverse from outer disorder. It has two arms of three kilometers long which are placed in Santo Stefano a Macerata in Italy. Virgo detector recorded scientific data from 2007 to 2011. To upgrade the Virgo suspension system the detection was shut down for a few months in 2010 and to begin the installation of Advanced Virgo the data taking with this final configuration for several months, the initial Virgo detector was shut down in September 2011.

In 2016 by joining the two advanced LIGO detectors the advanced Virgo started the commissioning system for the first "engineering" detecting period in 2017. On 14 August 2017 Virgo and LIGO pointed a signal as the of gravitational waves, GW170814 which was the first binary black hole combination detected by both Virgo and LIGO, and Just a few days later, GW170817 was detected by these two institutes. It was 10 times more sensory than the primary Virgo. In April 2019 Virgo started the "O_3" observation by further up-gradation.

B. Deep learning

Deep learning is a part of machine learning based on the Artificial Neural Network (ANN) and used for representation learning. The term "deep" refers to using multiple layers in a neural network. A deep learning network includes an input layer, one or more hidden layers, and an output layer (Figure 4). The input layer is used to get the input data such as an image. The input data passes through the activation before passing it to the next layer (first hidden layer). The input layer of a network contains weights to perform the multiplication operation on the input data. The hidden layers of a network are placed between the input and output layers. These layers perform the non-linear transformation on the data from the previous layer depending on activation functions and associated weights.

The output layer is responsible for computing and transferring the data from a network into the outside world. The output layer is designed to improve the network results with a repetitive process. The first working deep learning algorithms were represented by Alexey Ivakhnenko and Valentin Grigor′evich Lapa in 1967.[19] The working architectures of deep learning were built to be used for several computer vision applications with Neocognitron was represented by Kunihiko Fukushima in 1980.[20] The Deep Learning term was introduced by Rina Dechter in 1986.[21]

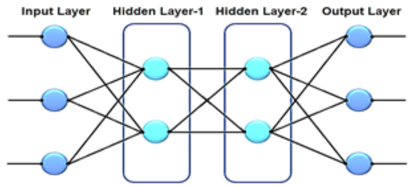

Figure 4 Deep neural network architecture.

At present time several types of architectures are used for deep learning, such as - deep neural network (DNN), deep belief network (DBN), recurrent neural network (RNN), Convolutional neural network (CNN), etc. Those architectures are commonly applied for several fields, such as - image classification, computer vision, speech recognition, audio recognition, natural language processing (NLP), machine translation, social network filtering, bioinformatics, medical image analysis, etc. In this paper, we use a CNN based learning system to classify gravitational waves of the dataset 'Gravity Spy' that is made up of the LIGO images. The Convolutional neural network (CNN) is a most commonly used deep learning networks to analyze visual imageries. The CNNs performs mathematical operation on image data known as convolution. CNN is built with some different types of layer including the Convolutional layer, pooling layer, and fully connected layer (Figure 5).

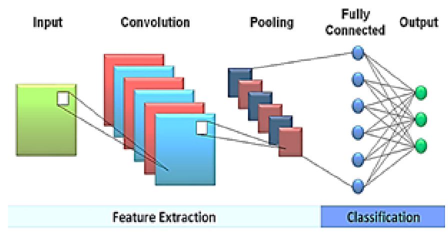

Figure 5 Basic architecture of CNN.

Methodology

In this section, we design and develop a deep learning system to classification gravitational waves of the dataset Gravity Spy (Gravitational waves) that is made up of the Laser Interferometer Gravitational-Wave Observatory (LIGO) images. Our system is divided into four blocks (Figure 6), those are- (1) Input, (2) Pre-processing, (3) Learning Network, and (4) Output. The input image block takes images from the dataset and sends them to the next block. The Pre-processing block processes the images from the input block and creates the input images in a suitable form for the Learning Network block. The Learning Network block has two-part, those are – (1) Convolution and (2) Classification. The convolution part is used to extract the important features from the pre-processed image, and then the Classification part classifies the gravitational wave from the images. And finally, the output block represents the class of the gravitational wave. The dataset images belong to 22 classes, represented in Figures 7 & 8.

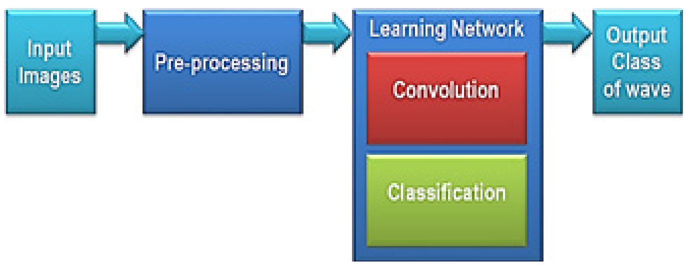

Figure 6 Block diagram.

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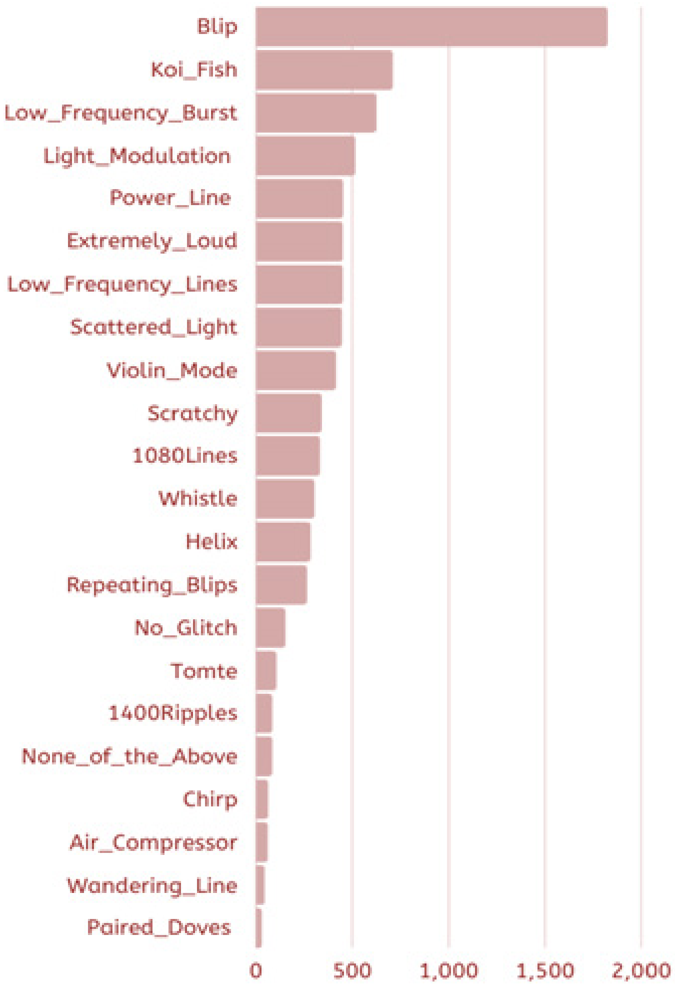

Figure 7 Classes with number of images in the training data.

C. Learning network architecture

To classify the Gravitational waves, we use a deep learning network model (Figure 9) with ten layers, including an input layer, two Convolutional layers, two BatchNormalyzation layers, two Pooling layers, a Flatten layer, a dense layer, and an output layer.

The architecture of the learning network includes two two-dimensional convolutional layers where I use filter_size=128 with karnel_size = (3,3), and hyperbolic tangent (tanh) activation function. Every convolutional layer is followed by a BatchNormalization layer and a two-dimensional Max-pool layer where pool_size = (2, 2).

Then we include a Flatten layer. And finally, we include a dense layer where we use units = 22, a Softmax activation function to get proper output (Table 1).

Results

To classify the Gravitational waves, we perform 11 epochs with 175 batches for training. The training results are represented in the Table 2.

The model accuracies and losses are plots in the Figures 10 & 11. Those figures represent the model performances for the training and the test for the first ten epochs. The model reaches stable performance after the ninth epoch.

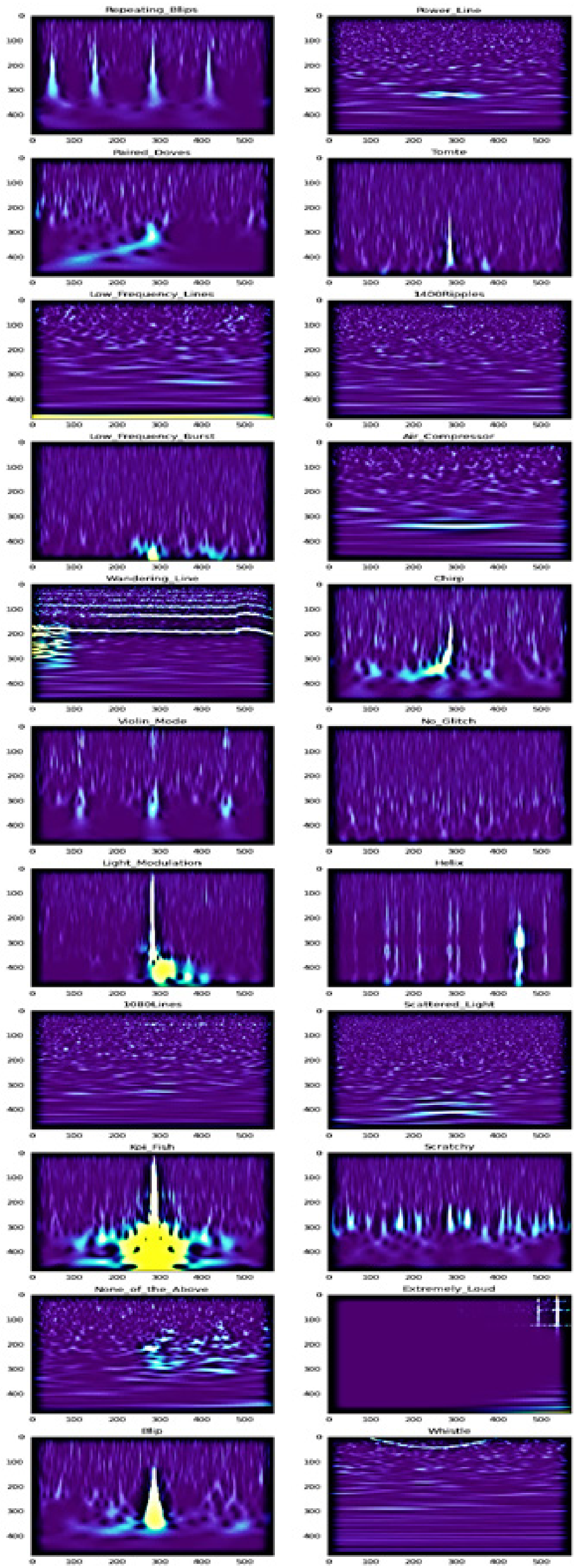

Figure 8 Sample images.

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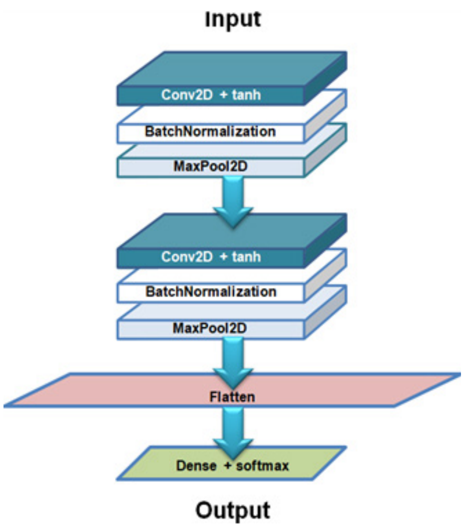

Figure 9 Network Architecture.

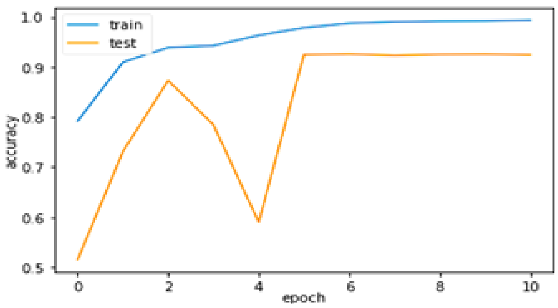

Figure 10 Model Accuracy.

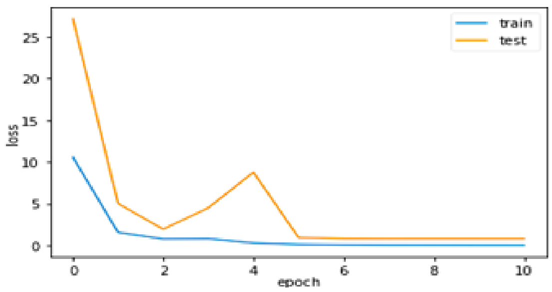

Figure 11 Model Loss.

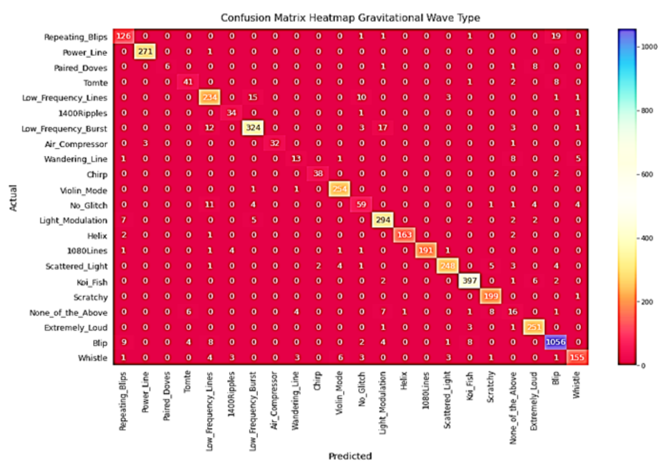

Figure 12 Confusion matrix heat-map.

Table 1 Network parameters

Layer No.	Layer (type)	Output Shape	Parameters
1	Conv2D	149, 149, 128	3584
2	Batch Normalization	149, 149, 128	512
3	Max Pooling	74, 74, 128	0
4	Conv2D	36, 36, 128	147584
5	Batch Normalization	36, 36, 128	512
6	Max Pooling	18, 18, 128	0
7	Flatten	41472	0
8	Dense	22	912406

Total Parameters: 1,064,598

Trainable Parameters: 1,064,086

Non-trainable Parameters: 512

To perform classification we divide the training images into 175 batches with batch size = 128.

Table 2 The training results

Epoch	Loss	Accuracy	Val_loss	Val_Accuracy
1	25.3115	0.6555	27.1153	0.5148
2	1.6086	0.9098	5.0185	0.7306
3	0.8317	0.9356	1.9504	0.8727
4	0.7452	0.9438	4.4937	0.7848
5	0.3067	0.9631	8.767	0.5896
6	0.1665	0.972	0.9504	0.9244
7	0.0645	0.9878	0.8137	0.9258
8	0.0504	0.9902	0.801	0.9229
9	0.0375	0.9918	0.8055	0.925
10	0.0348	0.9918	0.8027	0.9256
11	0.0313	0.9937	0.8026	0.9242

The accuracies of the model are-

Accuracy achieved: 93.26%

Accuracy by model: 99.34%

Accuracy by validation: 92.42%

Conclusion

In this paper, we review the Gravitational waves and implement a deep learning network system to classify the gravitational waves. The review of the Gravitational waves helps us to gain a piece of reasonable and useful knowledge about Gravitational waves and the Laser Interferometer Gravitational-Wave Observatory (LIGO). We believe the knowledge will help us to build another more effective and usable system. After performing the classification, we think my work reached its goals. According to the performance, we can say that our work is successful.

Authors contribution

The neural network architecture is designed and implements by Al Mahmud Al Mamun.

Al Mahmud Al Mamun and Md. Ashik Iqbal worked together to review and represent the classification of the gravitational wave using the deep learning technique.

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