Лабораторная работа №2. Введение в проектирование нейронных сетей с помощью Python По предмету "Киберфизические системы и технологии"

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Лабораторная работа №2. Введение в проектирование нейронных сетей с помощью Python

Одна из задач киберфизических систем - распознавание изображений с помощью машинного зрения. В этой лабораторной работе мы рассмотрим решение проблемы такого типа.

Мы будем использовать два файла данных с массивом рукописных чисел: mnist_train.csv и mnist_test.csv. Первый файл необходимо использовать для обучения нейронной сети, второй файл необходимо использовать для проверки работы нейронной сети. Каждый файл содержит строки (60000 в первом файле и 10000 во втором файле), в каждой из которых хранится массив размером 28x28 пикселей с цифровым изображением и номером, который соответствует изображению.

Основная задача - спроектировать нейронную сеть на Python, способную распознавать изображения чисел.

Для начала

[1]:
```python
"""
https://github.com/vedaant-varshney/ImageClassifierCNN/blob/master/
↪Image%20Classifier.ipynb

https://vitalflux.com/
↪different-types-of-cnn-architectures-explained-examples

https://sahiltinky94.medium.com/
↪know-about-googlenet-and-implementation-using-pytorch-92f827d675db
"""

from IPython.display import clear_output
import pandas as pd
import numpy as np
import matplotlib.pyplot as plt
import os
import random
import scipy
import torch
import torch.nn as nn
import torch.nn.functional as F
import gc
import torch.backends.cudnn

num_workers = 0
batch_size = 100
valid_size = 0.2
```

```
learning_rate = 0.01
learning_momentum = 0.9
MODEL_NAME = "LeNet"

torch.cuda.synchronize()
torch.cuda.empty_cache()
gc.collect()

torch.use_deterministic_algorithms(False)
torch.backends.cudnn.benchmark = True

print("Is cuda available?", torch.cuda.is_available())
print("Is cuDNN version:", torch.backends.cudnn.version())
print("cuDNN enabled? ", torch.backends.cudnn.enabled)
print("cuDNN benchmark?", torch.backends.cudnn.benchmark)
print("is Use Deterministic Algorithms?", torch.backends.cudnn.
 ↪deterministic)

cuda = torch.device('cuda')
print(torch.cuda.get_device_properties(cuda))
```

```
Is cuda available? True
Is cuDNN version: 8302
cuDNN enabled?  True
cuDNN benchmark? True
is Use Deterministic Algorithms? False
_CudaDeviceProperties(name='NVIDIA GeForce RTX 3080 Laptop GPU', major=8,
minor=6, total_memory=8191MB, multi_processor_count=48)
```

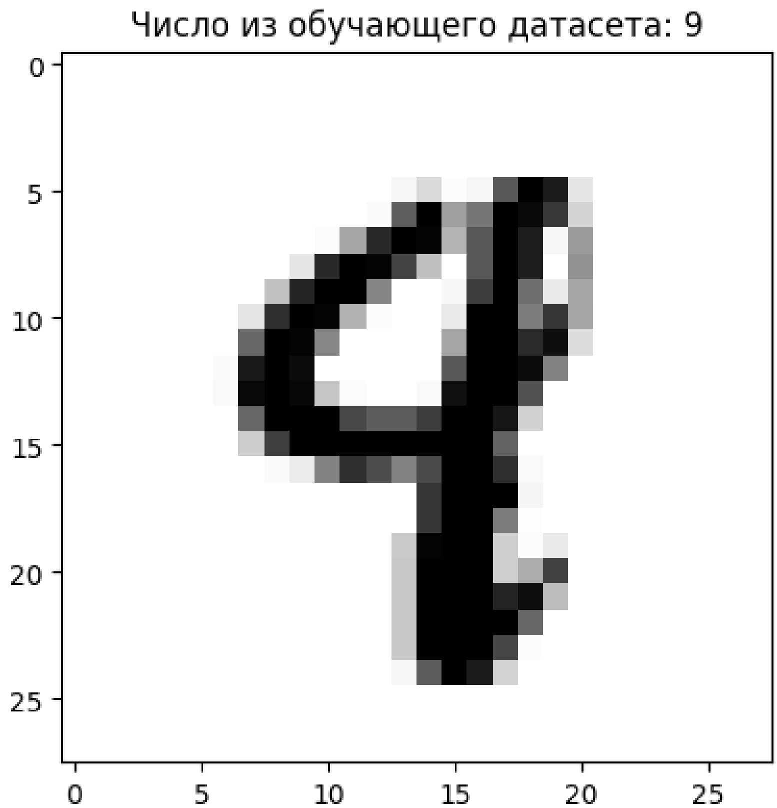
[2]:
```
# mnist_train = np.genfromtxt(f"dataset/mnist_train.csv", delimiter=',',␣
 ↪dtype=np.uint8)
# mnist_test = np.genfromtxt(f"dataset/mnist_test.csv", delimiter=',',␣
 ↪dtype=np.uint8)

mnist_train = pd.read_csv(f"dataset/mnist_train.csv", header=None,␣
 ↪engine="c", delimiter=',', dtype=np.uint8).to_numpy()
mnist_test = pd.read_csv(f"dataset/mnist_test.csv", header=None,␣
 ↪engine="c", delimiter=',', dtype=np.uint8).to_numpy()
```

[3]:
```
print(mnist_train.shape)
print(mnist_test.shape)

images_train = np.float32(np.reshape(mnist_train[:, 1:], (mnist_train.
 ↪shape[0], 28, 28, 1))) / 255
```

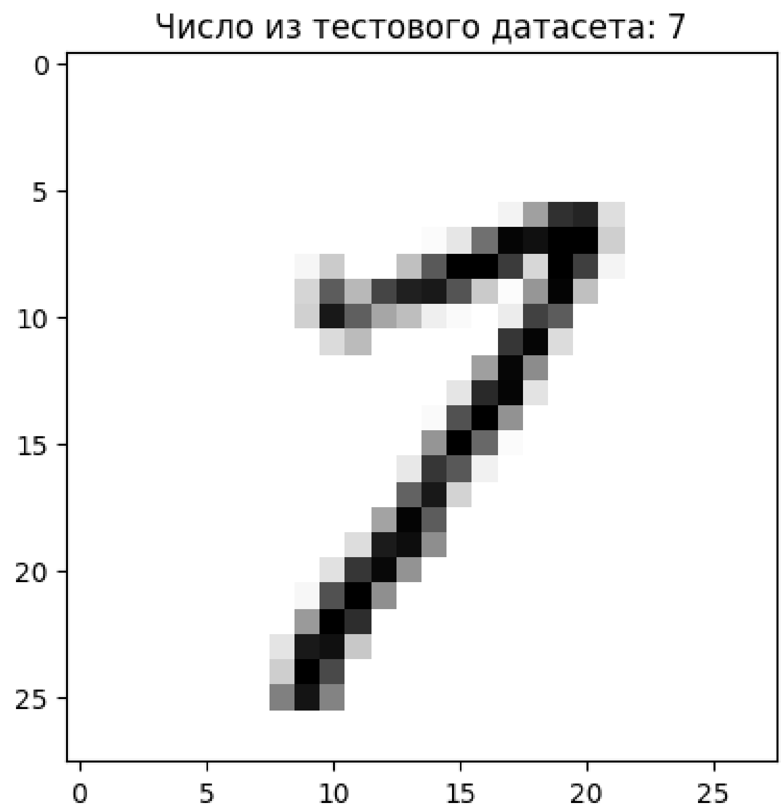
```
numbers_train = mnist_train[:, 0]
images_test = np.float32(np.reshape(mnist_test[:, 1:], (mnist_test.
 ↪shape[0], 28, 28, 1))) / 255
numbers_test = mnist_test[:, 0]

images_train = np.transpose(images_train, [0, 3, 1, 2])
images_test = np.transpose(images_test, [0, 3, 1, 2])

images_train = torch.tensor(images_train, device=cuda).
 ↪to(non_blocking=True)
numbers_train = torch.tensor(numbers_train, device=cuda).
 ↪to(non_blocking=True)
images_test = torch.tensor(images_test, device=cuda).to(non_blocking=True)
numbers_test = torch.tensor(numbers_test, device=cuda).
 ↪to(non_blocking=True)

print(images_train.shape)
print(numbers_train.shape)
print(images_test.shape)
print(numbers_test.shape)

print("Классы: ", np.unique(numbers_train.cpu()))
```

```
(60000, 785)
(10000, 785)
torch.Size([60000, 1, 28, 28])
torch.Size([60000])
torch.Size([10000, 1, 28, 28])
torch.Size([10000])
Классы:  [0 1 2 3 4 5 6 7 8 9]
```

[4]:
```
number_train = random.randint(0, images_test.cpu().shape[0])
plt.imshow(images_test.cpu()[number_train, 0, :, :], cmap=plt.cm.binary,␣
 ↪vmin=0, vmax=1)
plt.title(f"Число из обучающего датасета: {numbers_test.cpu().
 ↪numpy()[number_train]}")
print()
```



[5]:
```
number_test = random.randint(0, images_test.cpu().shape[0])
plt.imshow(images_test.cpu()[number_test, 0, :, :], cmap=plt.cm.binary,␣
 ↪vmin=0, vmax=1)
plt.title(f"Число из тестового датасета: {numbers_test.cpu().
 ↪numpy()[number_test]}")
print()
```



[6]:
```
print(images_train.shape)
print(numbers_train.shape)
```

```
torch.Size([60000, 1, 28, 28])
torch.Size([60000])
```

[7]:
```
from torchvision import datasets
import torchvision.transforms as transforms
from torch.utils.data.sampler import SubsetRandomSampler
from torch.utils.data import TensorDataset, DataLoader

from importlib import reload
import LeNet

reload(LeNet)

# Picking Fashion-MNIST dataset

train_transforms = transforms.Compose([
    transforms.RandomRotation(25),
```

```
    transforms.RandomInvert(p=0.5),
])
# transforms.RandomInvert(p=0.5),
normalize_transforms = transforms.Compose([
    transforms.Resize(size=LeNet.IMAGE_SIZE, interpolation=transforms.
 ↪InterpolationMode.BICUBIC),
    transforms.Normalize((0.5,), (0.5,)),
])
# transforms.Normalize((0.5,), (0.5,)),

train_data = TensorDataset(images_train, numbers_train)
test_data = TensorDataset(images_test, numbers_test)

# Finding indices for validation set
num_train = len(train_data)
indices = list(range(num_train))
#Randomize indices
np.random.shuffle(indices)

split = int(np.floor(num_train * valid_size))
train_index, test_index = indices[split:], indices[:split]

# Making samplers for training and validation batches
train_sampler = SubsetRandomSampler(train_index)
valid_sampler = SubsetRandomSampler(test_index)

# Creating data loaders
train_loader = torch.utils.data.DataLoader(train_data,␣
 ↪batch_size=batch_size, sampler=train_sampler,
                                           num_workers=num_workers)
valid_loader = torch.utils.data.DataLoader(train_data,␣
 ↪batch_size=batch_size, sampler=valid_sampler,
                                           num_workers=num_workers)
test_loader = torch.utils.data.DataLoader(test_data,␣
 ↪batch_size=batch_size, num_workers=num_workers)

# Image classes
classes = ['0', '1', '2', '3', '4', '5', '6', '7', '8', '9']
```

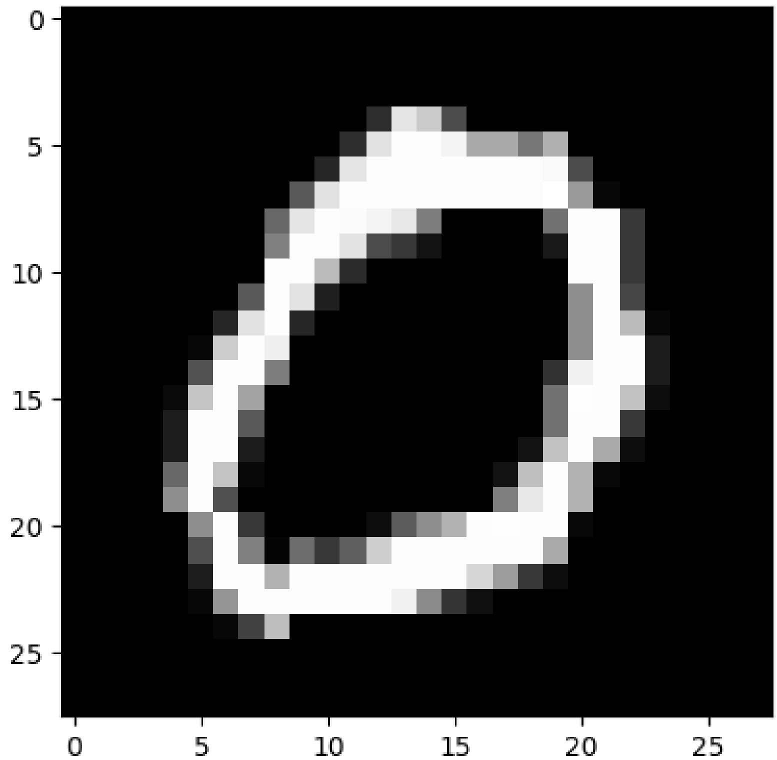
[8]:

```
for batch_index, (data, target) in enumerate(train_loader):
    break
print(data.shape, target.shape, classes[target[0]])
image = normalize_transforms(train_transforms(data.cpu()))
```

```python
plt.imshow(image[random.randint(0, image.shape[0]), 0, :, :], cmap=plt.cm.
 ↪binary, vmin=-1, vmax=1)
```

```
torch.Size([100, 1, 28, 28]) torch.Size([100]) 7
```

[8]:
```
<matplotlib.image.AxesImage at 0x1ea70355cf0>
```



[9]:
```python
from importlib import reload
import torchvision.models
import LeNet
import torch.optim as optim

reload(LeNet)

model = LeNet.LeNet()
model.cuda()
print(model)

# loss function (cross entropy loss)
criterion = nn.CrossEntropyLoss()
```

```
train_losses = []
valid_losses = []

# tracks validation loss change after each epoch
minimum_validation_loss = np.inf

# optimizer
optimizer = optim.SGD(model.parameters(), lr=learning_rate,␣
↪momentum=learning_momentum)
```

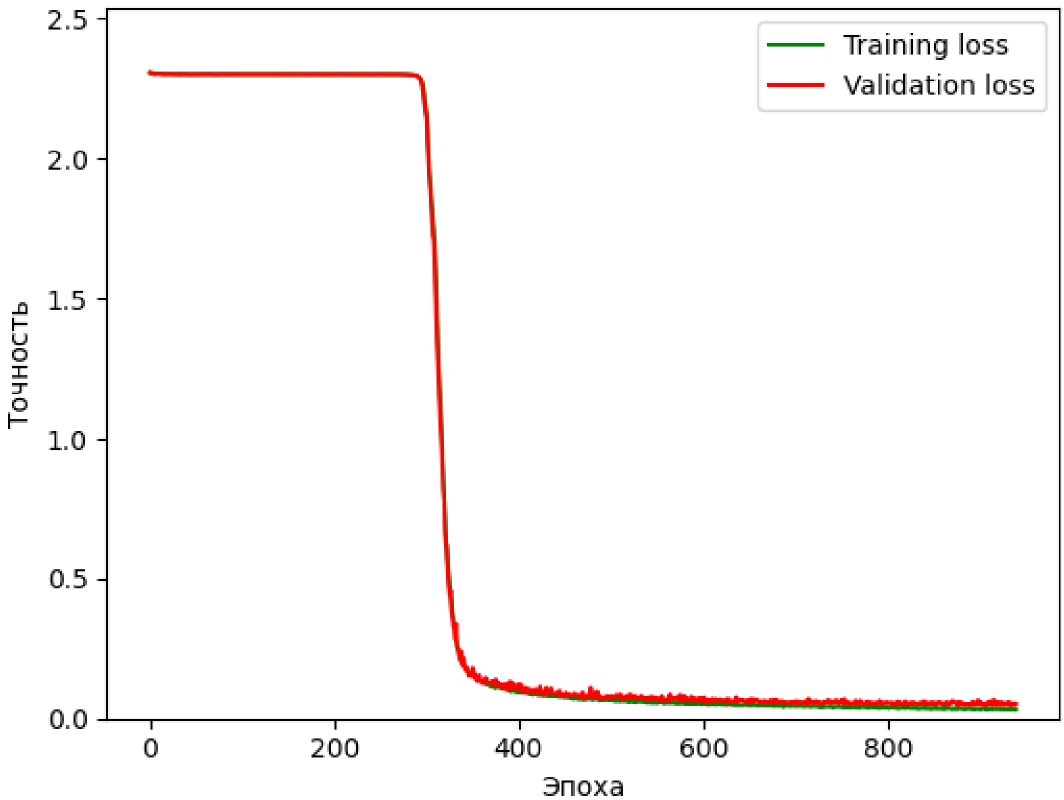
```
LeNet(
  (conv): Sequential(
    (0): Conv2d(1, 6, kernel_size=(5, 5), stride=(1, 1), padding=(2, 2))
    (1): Sigmoid()
    (2): AvgPool2d(kernel_size=(2, 2), stride=2, padding=0)
    (3): Conv2d(6, 16, kernel_size=(5, 5), stride=(1, 1))
    (4): Sigmoid()
    (5): AvgPool2d(kernel_size=(2, 2), stride=2, padding=0)
  )
  (fc): Sequential(
    (0): Linear(in_features=400, out_features=120, bias=True)
    (1): Sigmoid()
    (2): Linear(in_features=120, out_features=84, bias=True)
    (3): Sigmoid()
    (4): Linear(in_features=84, out_features=10, bias=True)
  )
)
```

[11]:
```
# epochs to train for
epochs = 1

for epoch in range(1, epochs + 1):
    clear_output(wait=True)

    train_loss = 0
    valid_loss = 0

    # training steps
    model.train()

    index = 0
    for batch_index, (data, target) in enumerate(train_loader):
        index += 1
        # clears gradients
        optimizer.zero_grad()
```

```
        # forward pass
        output = model(normalize_transforms(train_transforms(data)))
        # loss in batch
        loss = criterion(output, target)
        # backward pass for loss gradient
        loss.backward()
        # update paremeters
        optimizer.step()
        # update training loss
        train_loss += loss.item() * data.size(0)

    # validation steps
    model.eval()
    for batch_index, (data, target) in enumerate(valid_loader):
        # forward pass
        output = model(normalize_transforms(train_transforms(data)))
        # loss in batch
        loss = criterion(output, target)
        # update validation loss
        valid_loss += loss.item() * data.size(0)

    # average loss calculations
    train_loss = train_loss / len(train_loader.sampler)
    valid_loss = valid_loss / len(valid_loader.sampler)
    train_losses.append(train_loss)
    valid_losses.append(valid_loss)

    # Display loss statistics
    print(
        f'Текущая Эпоха: {len(train_losses)}\nTraining Loss: {round(train_loss, 6)}\nValidation Loss: {round(valid_loss, 6)}')

    # Saving model every time validation loss decreases
    if valid_loss <= minimum_validation_loss:
        print(f'Validation loss уменьшилась с {round(minimum_validation_loss, 6)} до {round(valid_loss, 6)}')
        torch.save(model.state_dict(), f'{MODEL_NAME}.pt')
        minimum_validation_loss = valid_loss
        print('Сохранение новой модели')

    plt.plot(train_losses, 'g')
    plt.plot(valid_losses, 'r')
    plt.ylim([0, max(np.max(np.array(train_losses)), np.max(np.array(train_losses)), 0.0) * 1.1])
```

```
    plt.xlabel("Эпоха")
    plt.ylabel("Точность")
    plt.legend(["Training loss", "Validation loss"])
    plt.show()
```

```
Текущая Эпоха: 940
Training Loss: 0.03266
Validation Loss: 0.052915
```



[91]:
```
from importlib import reload
import LeNet

reload(LeNet)

model_new = LeNet.LeNet()
model_new.cuda()
model_new.load_state_dict(torch.load(f'{MODEL_NAME}.pt'))

output_max = None
output_min = None
```

[97]:

```
# tracking test loss
test_loss = 0.0
class_correct = list(0. for i in range(10))
class_total = list(0. for i in range(10))

model_new.eval()

for batch_idx, (data, target) in enumerate(test_loader):
    # forward pass
    output = model_new(normalize_transforms(train_transforms(data)))

    local_max = np.max(output.detach().cpu().numpy(), axis=0)
    local_min = np.min(output.detach().cpu().numpy(), axis=0)
    if output_max is None:
        output_max = local_max
    else:
        output_max = np.max(np.array([local_max, output_max]), axis=0)
    if output_min is None:
        output_min = local_min
    else:
        output_min = np.min(np.array([local_min, output_min]), axis=0)

    # batch loss
    loss = criterion(output, target)
    # test loss update
    test_loss += loss.item() * data.size(0)
    # convert output probabilities to predicted class
    _, pred = torch.max(output, 1)
    # compare predictions to true label
    correct_tensor = pred.eq(target.data.view_as(pred))
    correct = np.squeeze(correct_tensor.numpy()) if not torch.cuda.
 ↪is_available() else np.squeeze(
        correct_tensor.cpu().numpy())
    # calculate test accuracy for each object class
    for i in range(len(target.data)):
        label = target.data[i]
        class_correct[label] += correct[i].item()
        class_total[label] += 1

# average test loss
test_loss = test_loss / len(test_loader.dataset)
print(f'Test Loss: {round(test_loss, 6)}')

for i in range(10):
```

```
    if class_total[i] > 0:
        print(f'Test Accuracy of {classes[i]}: {round(100 *␣
↪class_correct[i] / class_total[i], 2)}%')
    else:
        print(f'Test Accuracy of {classes[i]}s: N/A (no training␣
↪examples)')

print(
    f'Full Test Accuracy: {round(100. * np.sum(class_correct) / np.
↪sum(class_total), 2)}% {np.sum(class_correct)} out of {np.
↪sum(class_total)}')

output_max = np.array(output_max)
output_min = np.array(output_min)
print(f"output_min = {output_min}\noutput_max = {output_max}")
```

```
Test Loss: 0.040989
Test Accuracy of 0: 99.29%
Test Accuracy of 1: 99.3%
Test Accuracy of 2: 98.93%
Test Accuracy of 3: 98.81%
Test Accuracy of 4: 98.78%
Test Accuracy of 5: 98.88%
Test Accuracy of 6: 98.96%
Test Accuracy of 7: 98.05%
Test Accuracy of 8: 98.15%
Test Accuracy of 9: 97.22%
Full Test Accuracy: 98.64% 9864.0 out of 10000.0
output_min = [-12.405435 -10.730108 -12.911035 -12.028286 -11.388719 -11.
↪590592
 -18.247143 -13.193559  -7.603819 -10.83747 ]
output_max = [12.5716915 16.748579  19.614042  19.389887  18.39213   18.
↪968506
 17.291187  17.354427  18.150793  17.49377  ]
```

[104]:
```
prediction_threshold_amount = 1000
```

[107]:
```
prediction_threshold_low = []

while len(prediction_threshold_low) < prediction_threshold_amount:
    for batch_idx, (data, target) in enumerate(train_loader):
        clear_output(wait=True)
        data = normalize_transforms(train_transforms(data))
        output = model_new(data[:1, :1, :, :]).cpu().detach()
```

```
        output = np.divide(output.numpy()[0] - output_min, output_max -␣
 ↪output_min)
        if target[0] == np.argmax(output):
            continue
        prediction_threshold_low.append(np.max(output))
        print(
            f"calibration lower threshold {100 *␣
 ↪len(prediction_threshold_low) / prediction_threshold_amount:.2f}%")
        print(f"real value = {target[0]}")
        print(f"prediction = {np.argmax(output)}")
        print(f"prediction % = {np.max(output)}")
        print(f"predictions = {output}")
        plt.imshow(data.cpu()[0, 0, :, :], cmap=plt.cm.binary, vmin=-1,␣
 ↪vmax=1)
        plt.show()
        if len(prediction_threshold_low) >= prediction_threshold_amount:
            break

threshold_low = np.mean(np.array(prediction_threshold_low))
threshold_low_std = np.std(np.array(prediction_threshold_low))
clear_output(wait=True)
print(f"lower threshold = {threshold_low}\n with std =␣
 ↪{threshold_low_std}")
```

```
lower threshold = 0.6780125498771667
 with std = 0.07119216024875641
```

[108]:
```
prediction_threshold_high = []

while len(prediction_threshold_high) < prediction_threshold_amount:
    for batch_idx, (data, target) in enumerate(train_loader):
        clear_output(wait=True)
        data = normalize_transforms(train_transforms(data))
        output = model_new(data[:1, :1, :, :]).cpu().detach()
        output = np.divide(output.numpy()[0] - output_min, output_max -␣
 ↪output_min)
        if target[0] != np.argmax(output):
            continue
        prediction_threshold_high.append(np.max(output))
        print(
            f"calibration upper threshold {100 *␣
 ↪len(prediction_threshold_high) / prediction_threshold_amount:.2f}%")
        print(f"real value = {target[0]}")
        print(f"prediction = {np.argmax(output)}")
```

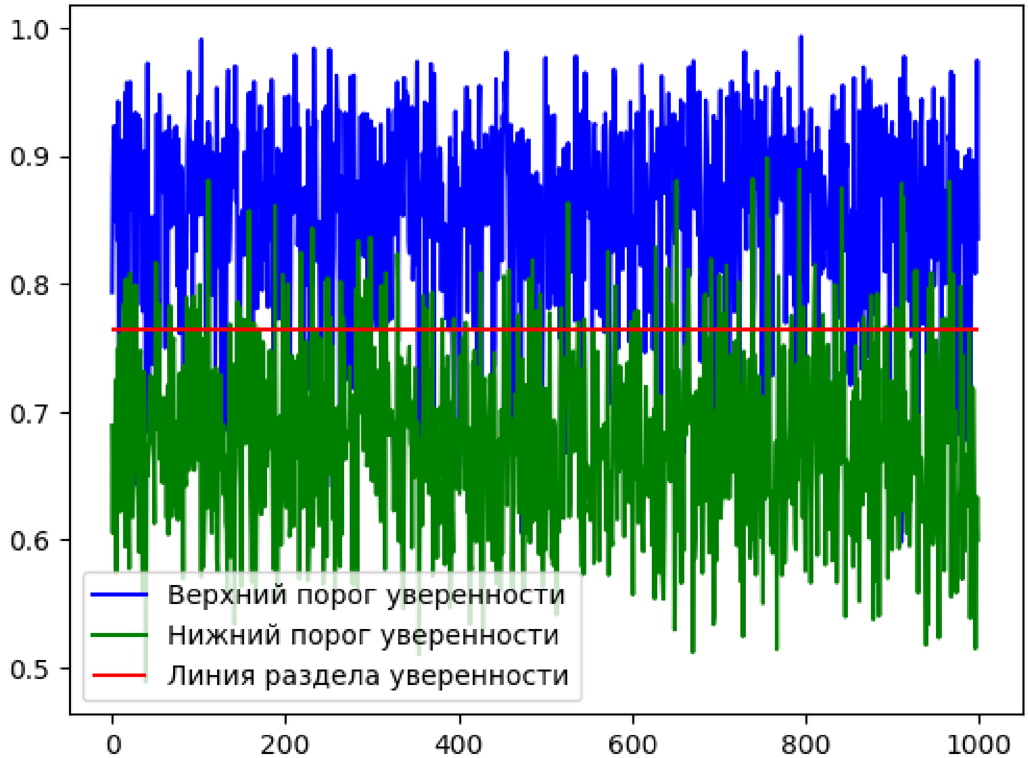
```
        print(f"prediction % = {np.max(output)}")
        print(f"predictions = {output}")
        plt.imshow(data.cpu()[0, 0, :, :], cmap=plt.cm.binary, vmin=-1,␣
↪vmax=1)
        plt.show()
        if len(prediction_threshold_high) >= prediction_threshold_amount:
            break

threshold_high = np.mean(np.array(prediction_threshold_high))
threshold_high_std = np.std(np.array(prediction_threshold_high))
clear_output(wait=True)
print(f"upper threshold = {threshold_high} with std =␣
↪{threshold_high_std}")
```

```
upper threshold = 0.8538323044776917 with std = 0.07443483918905258
```

[109]:

```
confidence_threshold = (threshold_high - threshold_high_std) / 2 +␣
↪(threshold_low + threshold_low_std) / 2

plt.plot(prediction_threshold_high, "b")
plt.plot(prediction_threshold_low, "g")
plt.hlines([confidence_threshold, ], xmin=0,␣
↪xmax=len(prediction_threshold_high), colors=["r", ])
plt.legend(["Верхний порог уверенности", "Нижний порог уверенности",␣
↪"Линия раздела уверенности"])

print(f"final confidence threshold = {confidence_threshold}")
print(f"from {threshold_low} => to {threshold_high}")
print(f"window = {threshold_high - threshold_low}")
print(f"output_min = {output_min}\noutput_max = {output_max}")
```

```
final confidence threshold = 0.7643010914325714
from 0.6780125498771667 => to 0.8538323044776917
window = 0.1758197546005249
output_min = [-12.405435 -10.730108 -12.911035 -12.028286 -11.388719 -11.
↪590592
 -18.247143 -13.193559  -7.603819 -10.83747 ]
output_max = [12.5716915 16.748579  19.614042  19.389887  18.39213   18.
↪968506
 17.291187  17.354427  18.150793  17.49377  ]
```



1.0
0.9
0.8
0.7
0.6
0.5
0
200
400
600
800
1000
Верхний порог уверенности
Нижний порог уверенности
Линия раздела уверенности


```
[ ]:
```