

Лабораторная работа N° 4

Сети с радиальными базисными элементами

Цель работы: исследование свойств некоторых видов сетей с радиальными базисными элементами, алгоритмов обучения, а также применение сетей в задачах классификации и аппроксимации функции.

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```
import numpy as np

import torch
import torch.nn as nn
from torch.utils.data import TensorDataset, DataLoader
import matplotlib.pyplot as plt

from sklearn.model_selection import train_test_split
```

Применение многослойной нейронной сети в задачах классификации

Функция, которая генерирует координаты точек эллипса по параметрическим уравнениям

```
def ellipse(t, a, b, x0, y0):
    x = x0 + a * np.cos(t)
    y = y0 + b * np.sin(t)
    return x, y

def parabola(t, p, x0, y0):
    x = x0 + p * t**2
    y = y0 + t
    return x, y
```

Функция, выполняющая поворот точек вокруг начала координат

```
def rotate(x, y, alpha):
    xr = x * np.cos(alpha) - y * np.sin(alpha)
    yr = x * np.sin(alpha) + y * np.cos(alpha)
    return xr, yr
```

Генерация равномерно распределенных значений от 0 до 2π включительно с общим количеством точек равным 200

```
t_for_ellipse = np.linspace(0, 2 * np.pi, 200)
t_for_parabola = np.linspace(-5, 5, 200)
```

Классы, выраженные эллипсами и параболой

```
# Класс 1
x1, y1 = ellipse(t_for_ellipse, a=0.4, b=0.15, x0=0.1, y0=-0.15)
x1, y1 = rotate(x1, y1, np.pi / 6.)

# Класс 2
x2, y2 = ellipse(t_for_ellipse, a=0.7, b=0.5, x0=0., y0=0.)
x2, y2 = rotate(x2, y2, -np.pi / 3.)

# Класс 3
x3, y3 = parabola(t_for_parabola, p=1, x0=-0.8, y0=0.)
x3, y3 = rotate(x3, y3, np.pi / 2.)
```

Создание списков points для каждого класса. Далее, создаются списки классов classes1, classes2, classes3 в формате one-hot encoding для каждого класса. Наконец, переменные X и Y объединяют все точки и соответствующие им классы для последующего использования в обучении многослойной нейронной сети.

```
points1 = [[x, y] for x, y in zip(x1, y1)]
points2 = [[x, y] for x, y in zip(x2, y2)]
points3 = [[x, y] for x, y in zip(x3, y3)]

classes1 = [[1., 0., 0.] for _ in range(len(points1))]
classes2 = [[0., 1., 0.] for _ in range(len(points2))]
classes3 = [[0., 0., 1.] for _ in range(len(points3))]

X = points1 + points2 + points3
Y = classes1 + classes2 + classes3
```

Разделение данных на обучающий (x_train, y_train) и тестовый (x_test, y_test) наборы. 20% данных будут использоваться для тестирования, а 80% - для обучения. Параметр random_state=42 фиксирует случайное разбиение, обеспечивая воспроизводимость результатов.

```
x_train, x_test, y_train, y_test = train_test_split(X, Y,
test_size=0.2, random_state=42)
```

Преобразование в тензоры

```
x_train = torch.FloatTensor(np.array(x_train))
y_train = torch.FloatTensor(np.array(y_train))

x_test = torch.FloatTensor(np.array(x_test))
y_test = torch.FloatTensor(np.array(y_test))
```

Через `train_loader` будем загружать на обучение батчи размером 10% от обучающего датасета.

```
train_dataset = TensorDataset(x_train, y_train)
test_dataset = TensorDataset(x_test, y_test)

batch_size = int(len(train_dataset) * 0.1)
train_loader = DataLoader(train_dataset, batch_size)
```

`l_norm` реализует вычисление L_p -нормы тензора `x` с параметром `p`, по умолчанию равным 2.

`rbf_multiquadric` представляет собой радиально-базисную функцию мультиквадратичного типа. Функция вычисляет значение $(1+x^2)^{1/2}$.

```
def l_norm(x, p=2):
    return torch.norm(x, p=p, dim=-1)

def rbf_multiquadric(x):
    return (1 + x.pow(2)).sqrt()
```

Реализация класса `RadialBasisFunctionNetwork`, который представляет собой слой с радиальными базисными функциями.

```
class RadialBasisFunctionNetwork(nn.Module):
    def __init__(self, in_features: int, num_kernels: int,
out_features: int):
        super(RadialBasisFunctionNetwork, self).__init__()
        self.in_features = in_features
        self.num_kernels = num_kernels
        self.out_features = out_features
        self._make_parameters()

        # Инициализация параметров слоя
        def _make_parameters(self):
            self.weights = nn.Parameter(torch.zeros(self.out_features,
self.num_kernels, dtype=torch.float32))
            self.kernels_centers =
nn.Parameter(torch.zeros(self.num_kernels, self.in_features,
dtype=torch.float32))
            self.log_shapes = nn.Parameter(torch.zeros(self.num_kernels,
dtype=torch.float32))
            self.reset()

        # Сброс параметров с заданными гиперпараметрами
        def reset(self, upper_bound_kernels: float = 1.0, std_shapes:
float = 0.1, gain_weights: float = 1.0):
            nn.init.uniform_(self.kernels_centers, a=-upper_bound_kernels,
b=upper_bound_kernels)
```

```

nn.init.normal_(self.log_shapes, mean=0.0, std=std_shapes)
nn.init.xavier_uniform_(self.weights, gain=gain_weights)

def forward(self, input: torch.Tensor):
    batch_size = input.size(0)

    # Рассчитываем расстояния до центров
    mu = self.kernels_centers.expand(batch_size, self.num_kernels,
self.in_features)
    diff = input.view(batch_size, 1, self.in_features) - mu

    # Применяем нормировочную функцию
    r = l_norm(diff)

    # Применяем параметр формы
    eps_r = self.log_shapes.exp().expand(batch_size,
self.num_kernels) * r

    # Применяем радиально-базисную функцию (мультиквадратичную)
    rbfs = rbf_multiquadric(eps_r)

    # В качестве ответа даем линейную комбинацию
    out = self.weights.expand(batch_size, self.out_features,
self.num_kernels) * rbfs.view(batch_size, 1, self.num_kernels)

    return out.sum(dim=-1)

# getter для центров базисных функций слоя
@property
def get_kernels_centers(self):
    return self.kernels_centers.detach()

# getter для весов слоя
@property
def get_weights(self):
    return self.weights.detach()

# getter для параметров формы слоя, представленные в
экспоненциальной форме
@property
def get_shapes(self):
    return self.log_shapes.detach().exp()

```

Создается экземпляр класса RadialBasisFunctionNetwork с двумя входными признаками, десятью базисными функциями и тремя выходными признаками. Функция потерь - MSE

```

rbf_net_classifier = RadialBasisFunctionNetwork(2, 10, 3)
loss_function = nn.MSELoss()
optimizer = torch.optim.Adam(rbf_net_classifier.parameters())

```

Внутри цикла по эпохам, для каждого батча, модель обновляется, вычисляется значение функции потерь и производится оптимизация параметров.

```
def fit(model, train_loader, criterion, optimizer, epochs):
    losses = []

    running_loss = 0.0
    processed_data = 0

    log_template = "\nEpoch {ep:03d} train_loss: {t_loss:0.4f}"
    for epoch in range(epochs):
        for inputs, labels in train_loader:
            optimizer.zero_grad()
            outp = model(inputs)

            loss = criterion(outp, labels)

            loss.backward()
            optimizer.step()

            running_loss += loss.item() * inputs.size(0)
            processed_data += inputs.size(0)

        train_loss = running_loss / processed_data
        losses.append(train_loss)
        print(log_template.format(ep=epoch+1, t_loss=loss))
    return losses
```

Выполняет предсказание с использованием модели, обученной на тестовых данных.

```
def predict(model, x_test):
    with torch.no_grad():
        model.eval()
        outp = model(x_test)
    return outp
```

Процесс обучения, который включает 2500 эпох.

```
losses = fit(rbf_net_classifier, train_loader, loss_function,
optimizer, 2500)
```

```
Epoch 001 train_loss: 57.1136
```

```
Epoch 002 train_loss: 49.8876
```

```
Epoch 003 train_loss: 43.5497
```

```
Epoch 004 train_loss: 37.9942
```

```
Epoch 005 train_loss: 33.1236
Epoch 006 train_loss: 28.8571
Epoch 007 train_loss: 25.1123
Epoch 008 train_loss: 21.8156
Epoch 009 train_loss: 18.9092
Epoch 010 train_loss: 16.3465
Epoch 011 train_loss: 14.0893
Epoch 012 train_loss: 12.1055
Epoch 013 train_loss: 10.3669
Epoch 014 train_loss: 8.8481
Epoch 015 train_loss: 7.5262
Epoch 016 train_loss: 6.3801
Epoch 017 train_loss: 5.3907
Epoch 018 train_loss: 4.5403
Epoch 019 train_loss: 3.8128
Epoch 020 train_loss: 3.1935
Epoch 021 train_loss: 2.6691
Epoch 022 train_loss: 2.2273
Epoch 023 train_loss: 1.8572
Epoch 024 train_loss: 1.5489
Epoch 025 train_loss: 1.2936
Epoch 026 train_loss: 1.0834
Epoch 027 train_loss: 0.9113
Epoch 028 train_loss: 0.7714
Epoch 029 train_loss: 0.6582
Epoch 030 train_loss: 0.5672
```

```
Epoch 031 train_loss: 0.4945
Epoch 032 train_loss: 0.4368
Epoch 033 train_loss: 0.3912
Epoch 034 train_loss: 0.3553
Epoch 035 train_loss: 0.3273
Epoch 036 train_loss: 0.3055
Epoch 037 train_loss: 0.2887
Epoch 038 train_loss: 0.2756
Epoch 039 train_loss: 0.2656
Epoch 040 train_loss: 0.2578
Epoch 041 train_loss: 0.2519
Epoch 042 train_loss: 0.2473
Epoch 043 train_loss: 0.2437
Epoch 044 train_loss: 0.2409
Epoch 045 train_loss: 0.2387
Epoch 046 train_loss: 0.2369
Epoch 047 train_loss: 0.2354
Epoch 048 train_loss: 0.2342
Epoch 049 train_loss: 0.2331
Epoch 050 train_loss: 0.2322
Epoch 051 train_loss: 0.2313
Epoch 052 train_loss: 0.2306
Epoch 053 train_loss: 0.2299
Epoch 054 train_loss: 0.2292
Epoch 055 train_loss: 0.2285
Epoch 056 train_loss: 0.2279
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Epoch 057 train_loss: 0.2273
Epoch 058 train_loss: 0.2267
Epoch 059 train_loss: 0.2261
Epoch 060 train_loss: 0.2255
Epoch 061 train_loss: 0.2249
Epoch 062 train_loss: 0.2244
Epoch 063 train_loss: 0.2238
Epoch 064 train_loss: 0.2233
Epoch 065 train_loss: 0.2227
Epoch 066 train_loss: 0.2222
Epoch 067 train_loss: 0.2217
Epoch 068 train_loss: 0.2211
Epoch 069 train_loss: 0.2206
Epoch 070 train_loss: 0.2201
Epoch 071 train_loss: 0.2196
Epoch 072 train_loss: 0.2191
Epoch 073 train_loss: 0.2186
Epoch 074 train_loss: 0.2181
Epoch 075 train_loss: 0.2176
Epoch 076 train_loss: 0.2172
Epoch 077 train_loss: 0.2167
Epoch 078 train_loss: 0.2162
Epoch 079 train_loss: 0.2158
Epoch 080 train_loss: 0.2153
Epoch 081 train_loss: 0.2149
Epoch 082 train_loss: 0.2144
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Epoch 083 train_loss: 0.2140
Epoch 084 train_loss: 0.2135
Epoch 085 train_loss: 0.2131
Epoch 086 train_loss: 0.2127
Epoch 087 train_loss: 0.2123
Epoch 088 train_loss: 0.2119
Epoch 089 train_loss: 0.2115
Epoch 090 train_loss: 0.2111
Epoch 091 train_loss: 0.2107
Epoch 092 train_loss: 0.2103
Epoch 093 train_loss: 0.2099
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Epoch 097 train_loss: 0.2084
Epoch 098 train_loss: 0.2080
Epoch 099 train_loss: 0.2076
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Epoch 104 train_loss: 0.2059
Epoch 105 train_loss: 0.2056
Epoch 106 train_loss: 0.2052
Epoch 107 train_loss: 0.2049
Epoch 108 train_loss: 0.2046
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Epoch 1642 train_loss: 0.0979
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Epoch 2422 train_loss: 0.0815

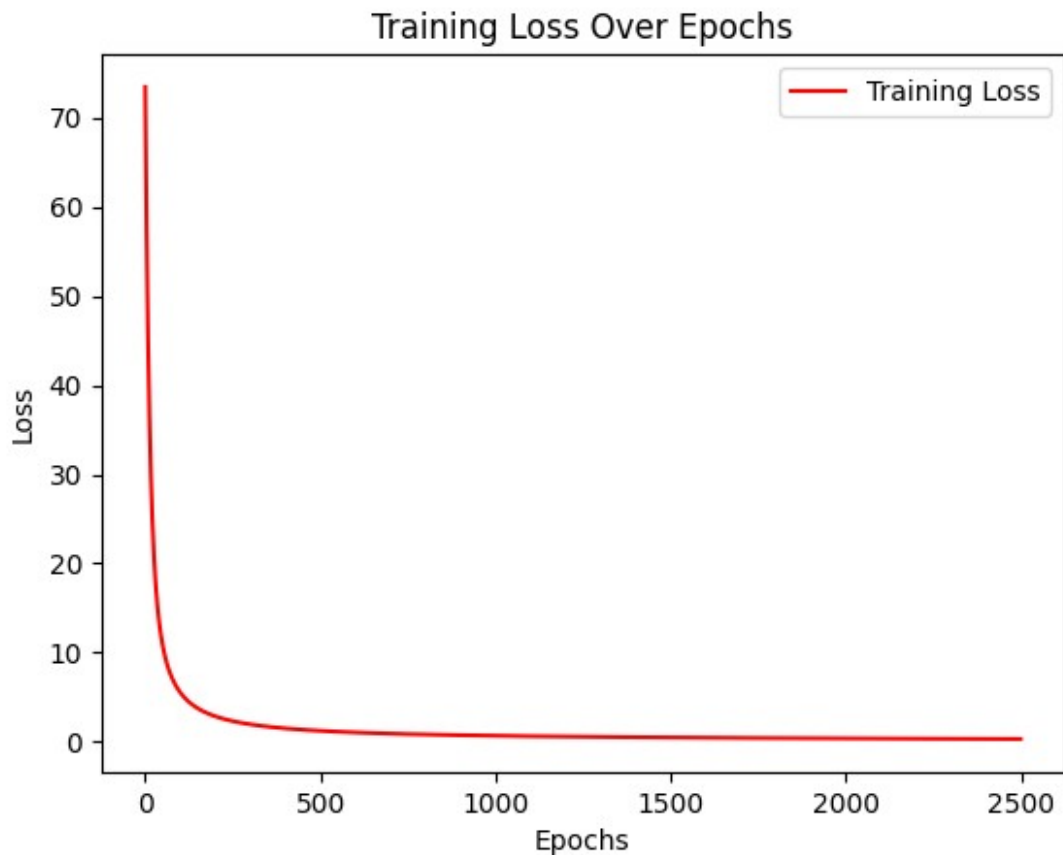
Epoch 2423 train_loss: 0.0815
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Epoch 2498 train_loss: 0.0807
Epoch 2499 train_loss: 0.0807
Epoch 2500 train_loss: 0.0806
```

График функции потерь (ошибка - MSE)

```
plt.plot(losses, color='red', label='Training Loss')
plt.legend()
plt.xlabel('Epochs')
plt.ylabel('Loss')
plt.title('Training Loss Over Epochs')
plt.show()
```



Формируется сетка точек для области $[-1, 1] \times [-1, 1]$ с использованием `np.linspace`, и каждая точка представляется парой координат x и y . Затем эти точки преобразуются в тензор, модель используется для предсказания цветовой компонент RGB для каждой точки. Результаты предсказаний сохраняются в переменной `predicted_RGB`, которая изменяется в форму $(200, 200, 3)$ для удобства последующего использования.

```
x_test = [[x, y] for x in np.linspace(-1, 1, 200) for y in
np.linspace(-1, 1, 200)]

x_test = torch.FloatTensor(np.array(x_test))

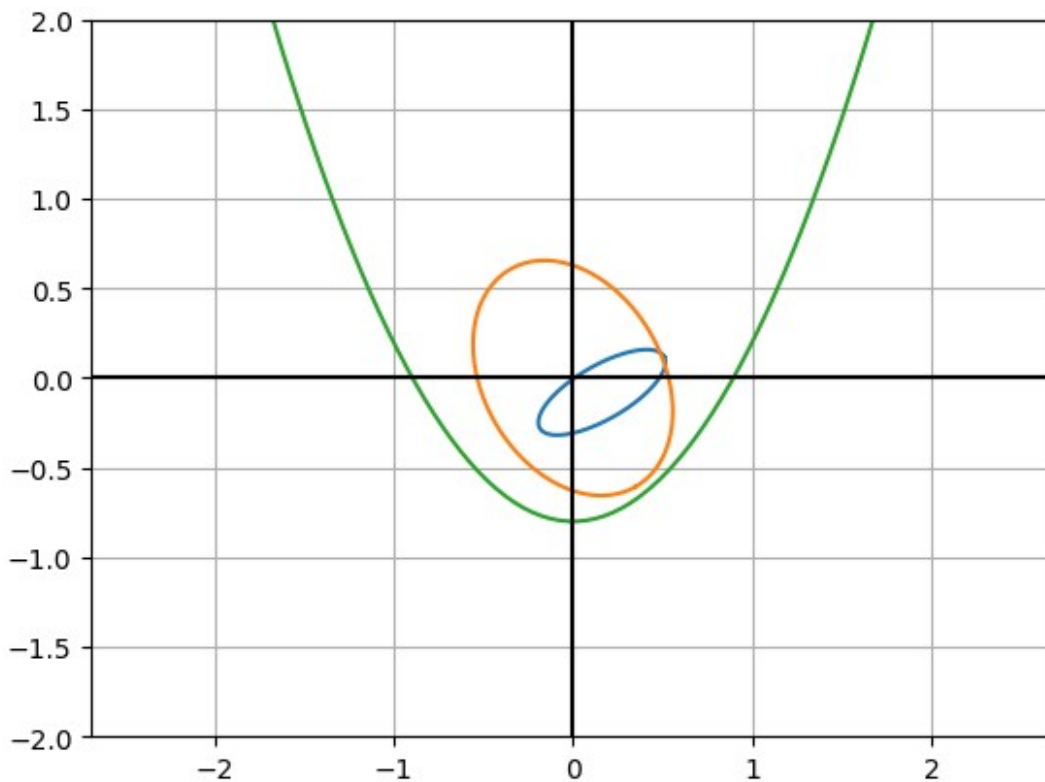
predicted_RGB = predict(rbf_net_classifier, x_test)
predicted_RGB = predicted_RGB.reshape((200, 200, 3))
```

Визуализация приведенных выше классов.

```
plt.plot(x1, y1)
plt.plot(x2, y2)
plt.plot(x3, y3)

plt.grid(True, which='both')
plt.axhline(y=0, color='k')
plt.axvline(x=0, color='k')

plt.axis('equal')
plt.xlim(-2, 2)
plt.ylim(-2, 2)
plt.show()
```

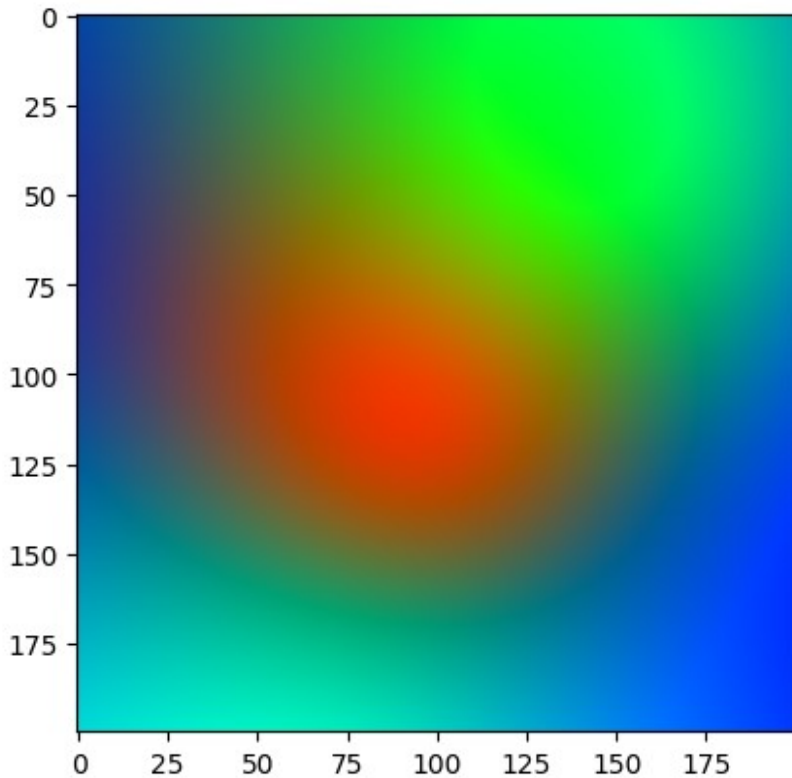


Разделение области на классы, которые линейно неразделимы

```
rotated_image = np.rot90(predicted_RGB)
flipped_image = np.fliplr(rotated_image)
plt.imshow(flipped_image)
```

Clipping input data to the valid range for imshow with RGB data ([0..1] for floats or [0..255] for integers).

<matplotlib.image.AxesImage at 0x224a0984eb0>



Применение многослойной нейронной сети в задачах аппроксимации функций

Функция для аппроксимации

```
def function(t):  
    return np.cos(-5 * t**2 + 10 * t - 5)
```

Создадим два набора точек - один разреженный, другой - эталонный

```
t1 = np.linspace(0, 2.5, 150)  
f1 = function(t1)  
  
t2 = np.linspace(0, 2.5, 2000)  
f2 = function(t2)
```

Преобразуем данные для обучения и тестирования в тензоры. Изменяем форму данных, чтобы соответствовать ожидаемому формату для использования в многослойной нейронной сети. Создается датасет для обучения, который будет использоваться при обучении сети.

```
x_train2 = torch.FloatTensor(t1)  
y_train2 = torch.FloatTensor(f1)
```



```
x_train2 = x_train2.view(-1, 1)
y_train2 = y_train2.view(-1, 1)
train_dataset2 = TensorDataset(x_train2, y_train2)

x_test2 = torch.FloatTensor(t2)
x_test2 = x_test2.view(-1, 1)
```

Наша сеть будет принимать на вход один признак, координату x , а на выходе будет выдавать значение функции в этой точке.

В качестве функции потерь берем `nn.MSELoss()`

```
rbf_net_approximator = RadialBasisFunctionNetwork(1, 35, 1)
loss_function = nn.MSELoss()
optimizer = torch.optim.Adam(rbf_net_approximator.parameters())
```

Экземпляр модели для решения задачи аппроксимации функции с одним входным признаком, 35 базисными функциями и одним выходным признаком.

```
batch_size = 10
train_loader2 = DataLoader(train_dataset2, batch_size)

losses2 = fit(rbf_net_approximator, train_loader2, loss_function,
optimizer, 2500)
```

Epoch 001 train_loss: 0.9694

Epoch 002 train_loss: 0.3726

Epoch 003 train_loss: 0.9874

Epoch 004 train_loss: 0.8506

Epoch 005 train_loss: 0.6349

Epoch 006 train_loss: 0.5831

Epoch 007 train_loss: 0.6005

Epoch 008 train_loss: 0.6087

Epoch 009 train_loss: 0.5985

Epoch 010 train_loss: 0.5859

Epoch 011 train_loss: 0.5767

Epoch 012 train_loss: 0.5687

Epoch 013 train_loss: 0.5603

Epoch 014 train_loss: 0.5518
Epoch 015 train_loss: 0.5433
Epoch 016 train_loss: 0.5351
Epoch 017 train_loss: 0.5271
Epoch 018 train_loss: 0.5192
Epoch 019 train_loss: 0.5114
Epoch 020 train_loss: 0.5038
Epoch 021 train_loss: 0.4964
Epoch 022 train_loss: 0.4891
Epoch 023 train_loss: 0.4820
Epoch 024 train_loss: 0.4751
Epoch 025 train_loss: 0.4683
Epoch 026 train_loss: 0.4617
Epoch 027 train_loss: 0.4552
Epoch 028 train_loss: 0.4489
Epoch 029 train_loss: 0.4428
Epoch 030 train_loss: 0.4368
Epoch 031 train_loss: 0.4309
Epoch 032 train_loss: 0.4252
Epoch 033 train_loss: 0.4197
Epoch 034 train_loss: 0.4143
Epoch 035 train_loss: 0.4090
Epoch 036 train_loss: 0.4039
Epoch 037 train_loss: 0.3989
Epoch 038 train_loss: 0.3940
Epoch 039 train_loss: 0.3893

Epoch 040 train_loss: 0.3847
Epoch 041 train_loss: 0.3802
Epoch 042 train_loss: 0.3758
Epoch 043 train_loss: 0.3715
Epoch 044 train_loss: 0.3674
Epoch 045 train_loss: 0.3634
Epoch 046 train_loss: 0.3594
Epoch 047 train_loss: 0.3556
Epoch 048 train_loss: 0.3519
Epoch 049 train_loss: 0.3483
Epoch 050 train_loss: 0.3448
Epoch 051 train_loss: 0.3414
Epoch 052 train_loss: 0.3380
Epoch 053 train_loss: 0.3348
Epoch 054 train_loss: 0.3317
Epoch 055 train_loss: 0.3286
Epoch 056 train_loss: 0.3256
Epoch 057 train_loss: 0.3227
Epoch 058 train_loss: 0.3199
Epoch 059 train_loss: 0.3172
Epoch 060 train_loss: 0.3145
Epoch 061 train_loss: 0.3120
Epoch 062 train_loss: 0.3095
Epoch 063 train_loss: 0.3070
Epoch 064 train_loss: 0.3047
Epoch 065 train_loss: 0.3024

Epoch 066 train_loss: 0.3001
Epoch 067 train_loss: 0.2980
Epoch 068 train_loss: 0.2959
Epoch 069 train_loss: 0.2938
Epoch 070 train_loss: 0.2918
Epoch 071 train_loss: 0.2899
Epoch 072 train_loss: 0.2880
Epoch 073 train_loss: 0.2862
Epoch 074 train_loss: 0.2845
Epoch 075 train_loss: 0.2827
Epoch 076 train_loss: 0.2811
Epoch 077 train_loss: 0.2795
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Epoch 081 train_loss: 0.2735
Epoch 082 train_loss: 0.2721
Epoch 083 train_loss: 0.2708
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Epoch 085 train_loss: 0.2682
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Epoch 087 train_loss: 0.2658
Epoch 088 train_loss: 0.2647
Epoch 089 train_loss: 0.2636
Epoch 090 train_loss: 0.2625
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Epoch 092 train_loss: 0.2604
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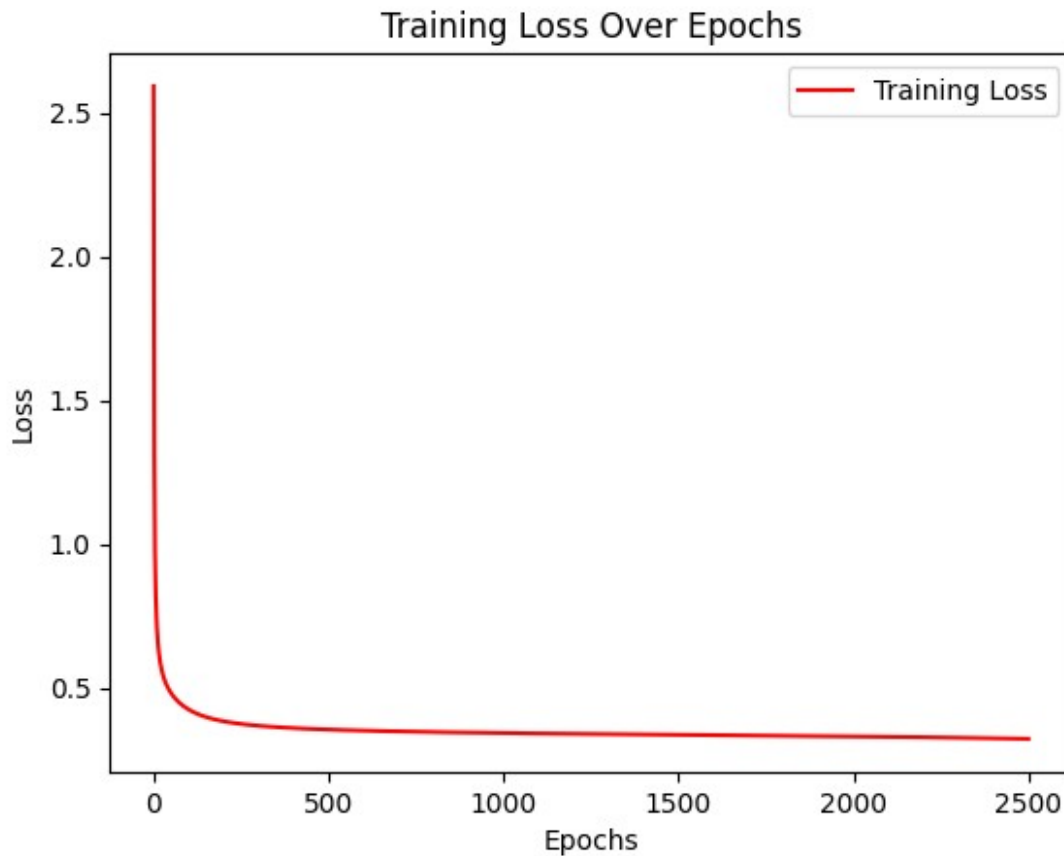
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Epoch 2465 train_loss: 0.2432
Epoch 2466 train_loss: 0.2433
Epoch 2467 train_loss: 0.2434
Epoch 2468 train_loss: 0.2435
Epoch 2469 train_loss: 0.2436
Epoch 2470 train_loss: 0.2437
Epoch 2471 train_loss: 0.2438
Epoch 2472 train_loss: 0.2439
Epoch 2473 train_loss: 0.2440
Epoch 2474 train_loss: 0.2441
Epoch 2475 train_loss: 0.2441
Epoch 2476 train_loss: 0.2442
Epoch 2477 train_loss: 0.2443
Epoch 2478 train_loss: 0.2444
Epoch 2479 train_loss: 0.2445
Epoch 2480 train_loss: 0.2446
Epoch 2481 train_loss: 0.2447
Epoch 2482 train_loss: 0.2448
Epoch 2483 train_loss: 0.2449


```
Epoch 2484 train_loss: 0.2450
Epoch 2485 train_loss: 0.2451
Epoch 2486 train_loss: 0.2452
Epoch 2487 train_loss: 0.2453
Epoch 2488 train_loss: 0.2454
Epoch 2489 train_loss: 0.2455
Epoch 2490 train_loss: 0.2456
Epoch 2491 train_loss: 0.2457
Epoch 2492 train_loss: 0.2458
Epoch 2493 train_loss: 0.2459
Epoch 2494 train_loss: 0.2460
Epoch 2495 train_loss: 0.2461
Epoch 2496 train_loss: 0.2462
Epoch 2497 train_loss: 0.2463
Epoch 2498 train_loss: 0.2464
Epoch 2499 train_loss: 0.2464
Epoch 2500 train_loss: 0.2465
```

График функции потерь (ошибка - MSE)

```
plt.plot(losses2, color='red', label='Training Loss')
plt.legend()
plt.xlabel('Epochs')
plt.ylabel('Loss')
plt.title('Training Loss Over Epochs')
plt.show()
```



Соберем предсказания модели

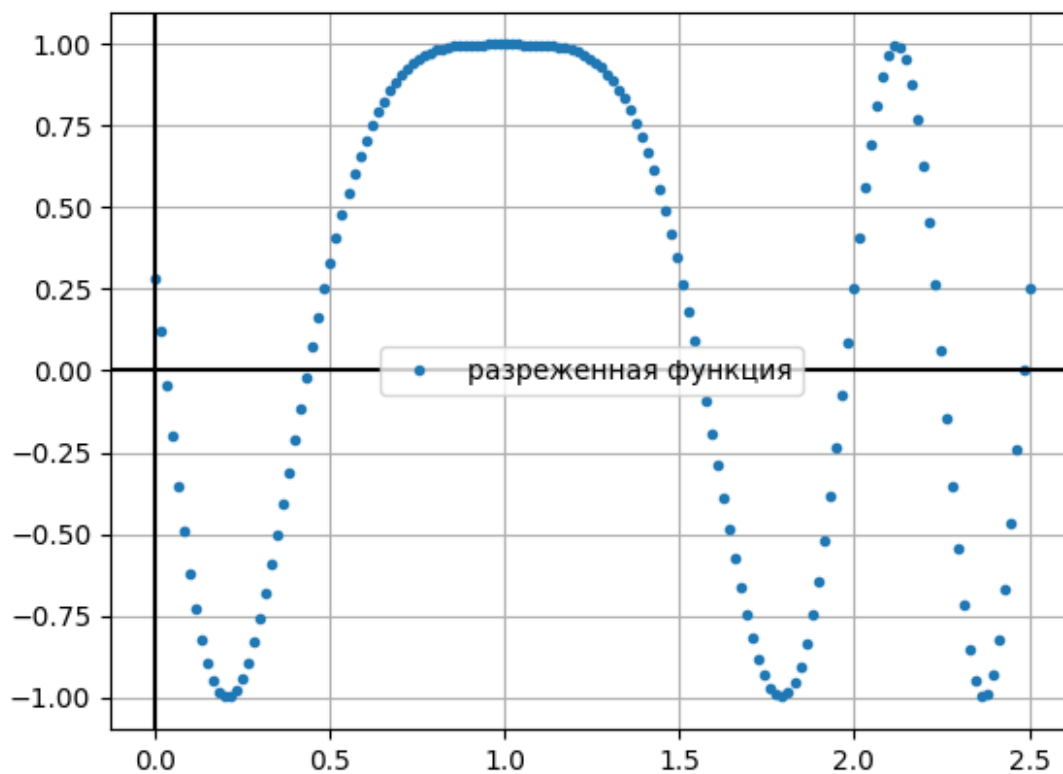
```
f2_pred = predict(rbf_net_approximator, x_test2)
```

С помощью метода `get_kernels_centers` получаем центры базисных функций из обученной многослойной нейронной сети, затем, с использованием функции `predict`, выполняется предсказание для полученных центров, результат записывается в переменную `mu_y`.

```
mu_x = rbf_net_approximator.get_kernels_centers  
mu_y = predict(rbf_net_approximator, mu_x)
```

Сравнение разреженного варианта, приближения и истинной функции

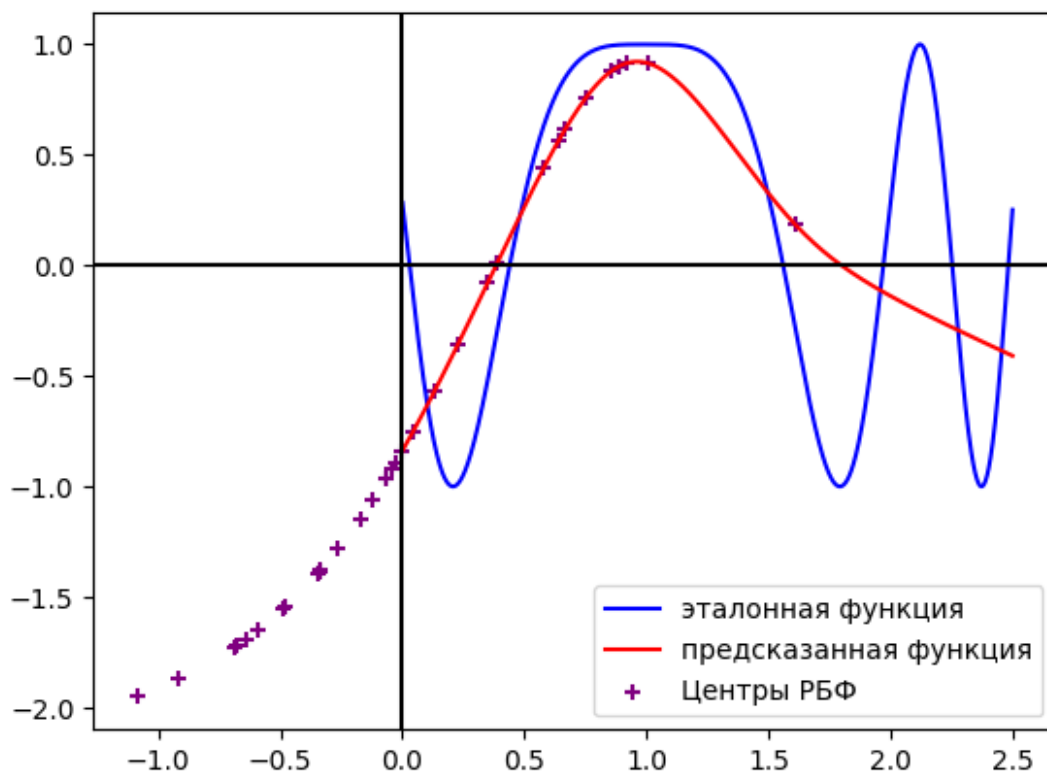
```
plt.plot(t1, f1, '.', label='разреженная функция')  
  
plt.grid(True, which='both')  
plt.axhline(y=0, color='k')  
plt.axvline(x=0, color='k')  
  
plt.legend()  
plt.show()
```



```
plt.plot(t2, f2, color="blue", label='эталонная функция')
plt.plot(t2, f2_pred, color="red", label='предсказанная функция')
plt.scatter(mu_x, mu_y, color="purple", marker='+', label='Центры РБФ')

plt.axhline(y=0, color='k')
plt.axvline(x=0, color='k')

plt.legend()
plt.show()
```



Выводы: В ходе данной работы была построена сеть на основе радиально-базисной функции, которая успешно применялась для решения задач классификации и аппроксимации функций. После обучения на протяжении 2500 эпох получены обнадеживающие результаты, что свидетельствует о эффективности предложенного метода.

Стоит отметить, что несмотря на хорошую способность к аппроксимации сложных нелинейных функций, выбор правильных центров RBF является очень важным шагом в процессе обучения и может доставлять немало проблем своим влиянием на производительность сети.