

KAN Kolmogorov Arnold Network Note

研究任務

1. 閱讀 KAN Kolmogorov-Arnold Network 論文
2. 設計 KAN 網路系統階層式架構 IDEF0
3. 設計 KAN 網路系統每個功能模組離散事件建模 Grafcet
4. 以 MIAT 方法論合成每個 Grafcet 控制器電路
5. 以 ChatGPT 合成每個 Grafcet Datapath 電路
6. FPGA 整合驗證

⚠ Attention

Kolmogorov-Arnold Network 之研究任務須於六月底完成，作為暑期實習前置條件。

✍ Seealso

「20240527」目標預定之所有（第一到第六點）研究任務，當前初版皆已完成，接下來主要目標為模型量化和優化相關電路設計及輸出結果。

- 「20240610」Integer Quantization 部分已完成優化改寫。
- 「20240617」KAN Pipeline Grafcet 完成初版架構設計。
- 「20240619」Verilog Design 部分進行調整，解決 Testbench 計算後輸出為零的問題。

開放原始碼參考

- Open Source Code: <https://github.com/KindXiaoming/pykan>
- Research Paper Reference: <https://arxiv.org/abs/2404.19756>

論文內容統整

📄 Summary

KAN (Kolmogorov-Arnold Network) 論文基本概念。

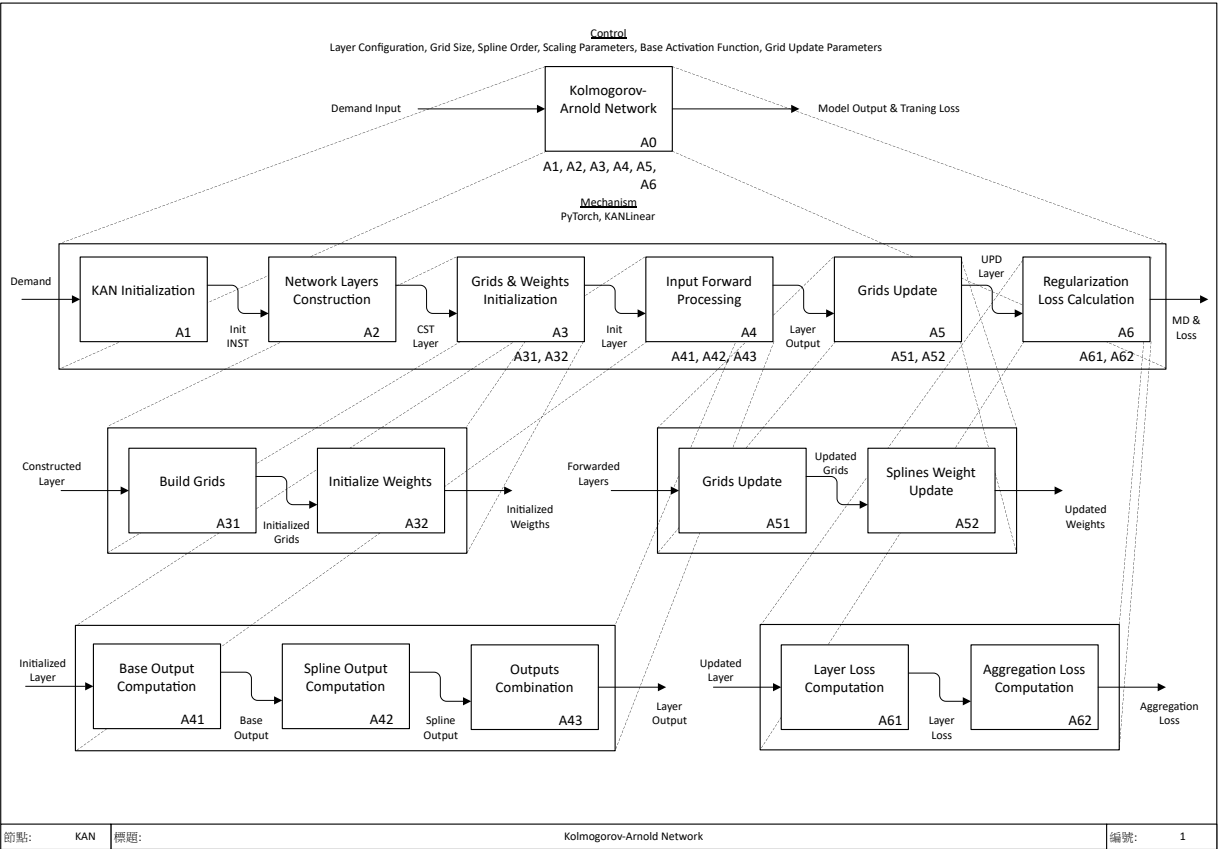
1. Research Background
 - Kolmogorov-Arnold Representation Theorem (KART)：此定理說明任何多變量的連續函數都可以表示為單變量連續函數和加法操作的有限組合。
 - Limitations of Multi-Layer Perceptron (MLP)：傳統由 MLP 形成的神經網路雖然具有強大的表達能力，但在某些應用中存在固定的 Activation Function，使得其解釋性較差且參數效率低下。
2. Kolmogorov-Arnold Network (KAN)
 - Network Structure：與 MLP 不同，KAN 在 Edge (即權重) 上使用可學習的 Activation Function，而不是在 Node (即神經元) 上使用固定的 Activation Function。
 - Activation Function：KAN 中的每個權重參數被替換為一個參數化為樣條函數的單變量函數。節點只進行簡單的信號相加操作，不應用任何非線性操作。
3. Advantages of KAN
 - Higher Precision：KAN 在數據擬合和偏微分方程求解方面比 MLP 更準確。例如，在偏微分方程求解中，一個兩層且寬度為十的 KAN 比一個四層且寬度為一百的 MLP 準確度高百倍。
 - Explainability：KAN 可以直觀地可視化，並能與人類用戶進行互動，有助於科學家重新發現數學和物理定律。

📄 Summary

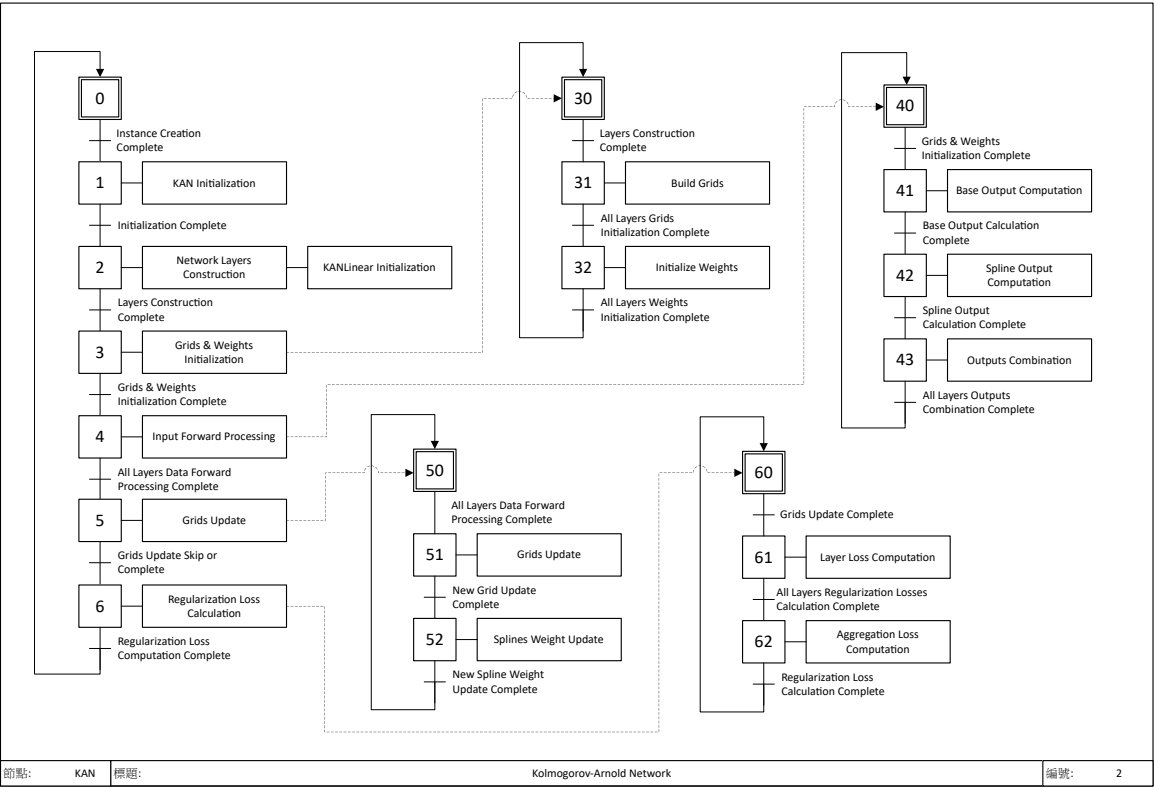
KAN (Kolmogorov-Arnold Network) 和 MLP (Multi-Layer Perceptron) 之間的主要差異與比較。

1. 激活函数的位置 and 特性
 - MLP: 激活函数固定, 位于节点 (神经元) 上; 且激活函数一般是非线性函数, 例如 ReLU、Sigmoid 等。
 - KAN: 激活函数是可学习的, 位于边 (权重) 上; 且每个权重参数被替换为一个参数化为样条函数的单变量函数。
2. 网络结构和权重表示
 - MLP: 使用线性权重矩阵进行计算, 然后应用固定的非线性激活函数; 节点进行非线性变换。
 - 结构公式:
$$MLP(x) = ((W3 \circ \sigma2 \circ W2 \circ \sigma1 \circ W1)(x))$$
 - KAN: 没有线性权重矩阵, 所有权重都被样条函数替代; 节点仅进行简单的信号相加操作, 不进行非线性变换。
 - 结构公式:
$$KAN(x) = ((\Phi3 \circ \Phi2 \circ \Phi1)(x))$$
3. 训练方法和参数优化
 - MLP: 权重矩阵通过梯度下降法进行训练; 训练过程需要调整大量的线性权重参数。
 - KAN: 核心在于样条函数的参数化和学习; 样条函数通过调整其参数进行优化。
4. 表达能力和适用范围
 - MLP: 基于普适近似定理, MLP 能够逼近任意连续函数; 常用于各种回归和分类问题, 但在高维数据下可能效率低下。
 - KAN: 基于 Kolmogorov-Arnold 表示定理, 能够表达高维数据的组合结构和单变量函数; 对于需要高精度度和解释性的应用, 如数学模型和物理模型, 有显著优势。
5. 可解释性和直观性
 - MLP: 由于固定的激活函数和复杂的权重矩阵, MLP 在解释性方面较为薄弱; 解释模型需要额外的工具和方法, 如 SHAP、LIME 等。
 - KAN: 由于激活函数是可学习的单变量函数, KAN 的结构更易于直观理解; KAN 的节点仅进行信号相加, 使得整体网络更易于可视化和解释。
6. 计算和资源需求
 - MLP: 训练和推理过程中, 计算资源需求较大, 特别是在高维数据和大模型情况下。
 - KAN: 由于样条函数的引入, KAN 在同样精度度下所需的参数和计算资源相对较少; 能够在较小的计算图上达到与大型 MLP 相同甚至更好的精度度。

設計階層式架構 IDEF0



設計功能模組離散事件建模 Grafcet



Python 模擬驗證

- 基於 IDEFO 和 Grafcet 重構後之 Kolmogorov-Arnold Network (PyTorch)

```
import math

import torch
import torch.nn.functional as F

class KANLinear(torch.nn.Module):
    def __init__(
        self,
        in_features,
        out_features,
        grid_size=5,
        spline_order=3,
        scale_base=1.0,
        scale_spline=1.0,
        enable_standalone_scale_spline=True,
        base_activation=torch.nn.SiLU,
        grid_eps=0.02,
        grid_range=[-1, 1],
    ):
        super(KANLinear, self).__init__()
        self.in_features = in_features
        self.out_features = out_features
        self.grid_size = grid_size
        self.spline_order = spline_order

        # 構建網格點
        self.grid = self.build_grid(grid_range, grid_size, spline_order)

        # 初始化基礎權重和樣條權重
        self.base_weight, self.spline_weight, self.spline_scaler = self.initialize_weights()
```

```

        out_features, in_features, grid_size, spline_order, scale_base, scale_spline,
        enable_standalone_scale_spline
    )

    self.scale_base = scale_base
    self.scale_spline = scale_spline
    self.enable_standalone_scale_spline = enable_standalone_scale_spline
    self.base_activation = base_activation()
    self.grid_eps = grid_eps

def build_grid(self, grid_range, grid_size, spline_order):
    h = (grid_range[1] - grid_range[0]) / grid_size
    grid = (
        torch.arange(-spline_order, grid_size + spline_order + 1) * h
        + grid_range[0]
    )
    .expand(self.in_features, -1)
    .contiguous()
)
return grid

def initialize_weights(self, out_features, in_features, grid_size, spline_order, scale_base, scale_spline,
                       enable_standalone_scale_spline):
    base_weight = torch.nn.Parameter(torch.Tensor(out_features, in_features))
    spline_weight = torch.nn.Parameter(
        torch.Tensor(out_features, in_features, grid_size + spline_order)
    )
    if enable_standalone_scale_spline:
        spline_scaler = torch.nn.Parameter(
            torch.Tensor(out_features, in_features)
        )
    else:
        spline_scaler = None
    torch.nn.init.kaiming_uniform_(base_weight, a=math.sqrt(5) * scale_base)
    torch.nn.init.kaiming_uniform_(spline_weight, a=math.sqrt(5) * scale_spline)
    if enable_standalone_scale_spline:
        torch.nn.init.kaiming_uniform_(spline_scaler, a=math.sqrt(5) * scale_spline)
    return base_weight, spline_weight, spline_scaler

def b_splines(self, x: torch.Tensor):
    bases = self.calculate_b_spline_bases(x)
    return bases.contiguous()

def calculate_b_spline_bases(self, x: torch.Tensor):
    grid: torch.Tensor = (
        self.grid
    ) # (in_features, grid_size + 2 * spline_order + 1)
    x = x.unsqueeze(-1)
    bases = ((x ≥ grid[:, :-1]) & (x < grid[:, 1:])).to(x.dtype)
    for k in range(1, self.spline_order + 1):
        bases = (
            (x - grid[:, : -(k + 1)])
            / (grid[:, k:-1] - grid[:, : -(k + 1)])
            * bases[:, :, :-1]
        ) + (
            (grid[:, k + 1:] - x)
            / (grid[:, k + 1:] - grid[:, 1:(-k)])
            * bases[:, :, 1:]
        )
    return bases

def curve2coeff(self, x: torch.Tensor, y: torch.Tensor):
    A = self.b_splines(x).transpose(
        0, 1
    ) # (in_features, batch_size, grid_size + spline_order)
    B = y.transpose(0, 1) # (in_features, batch_size, out_features)
    solution = torch.linalg.lstsq(
        A, B
    ).solution # (in_features, grid_size + spline_order, out_features)
    result = solution.permute(

```

```

        2, 0, 1
    ) # (out_features, in_features, grid_size + spline_order)
    return result.contiguous()

@property
def scaled_spline_weight(self):
    if self.enable_standalone_scale_spline:
        return self.spline_weight * self.spline_scaler.unsqueeze(-1)
    else:
        return self.spline_weight

def forward(self, x: torch.Tensor):
    base_output = self.compute_base_output(x)
    spline_output = self.compute_spline_output(x)
    return base_output + spline_output

def compute_base_output(self, x: torch.Tensor):
    return F.linear(self.base_activation(x), self.base_weight)

def compute_spline_output(self, x: torch.Tensor):
    return F.linear(
        self.b_splines(x).view(x.size(0), -1),
        self.scaled_spline_weight.view(self.out_features, -1),
    )

@torch.no_grad()
def update_grid(self, x: torch.Tensor, margin=0.01):
    batch = x.size(0)

    splines = self.b_splines(x) # (batch, in, coeff)
    splines = splines.permute(1, 0, 2) # (in, batch, coeff)
    orig_coeff = self.scaled_spline_weight # (out, in, coeff)
    orig_coeff = orig_coeff.permute(1, 2, 0) # (in, coeff, out)
    unreduced_spline_output = torch.bmm(splines, orig_coeff) # (in, batch, out)
    unreduced_spline_output = unreduced_spline_output.permute(
        1, 0, 2
    ) # (batch, in, out)

    x_sorted = torch.sort(x, dim=0)[0]
    grid_adaptive = x_sorted[
        torch.linspace(
            0, batch - 1, self.grid_size + 1, dtype=torch.int64, device=x.device
        )
    ]

    uniform_step = (x_sorted[-1] - x_sorted[0] + 2 * margin) / self.grid_size
    grid_uniform = (
        torch.arange(
            self.grid_size + 1, dtype=torch.float32, device=x.device
        ).unsqueeze(1)
        * uniform_step
        + x_sorted[0]
        - margin
    )

    grid = self.grid_eps * grid_uniform + (1 - self.grid_eps) * grid_adaptive
    grid = torch.concatenate(
        [
            grid[:1]
            - uniform_step
            * torch.arange(self.spline_order, 0, -1, device=x.device).unsqueeze(1),
            grid,
            grid[-1:]
            + uniform_step
            * torch.arange(1, self.spline_order + 1, device=x.device).unsqueeze(1),
        ],
        dim=0,
    )

    self.grid.copy_(grid.T)
    self.spline_weight.data.copy_(self.curve2coeff(x, unreduced_spline_output))

```

```

def regularization_loss(self, regularize_activation=1.0, regularize_entropy=1.0):
    l1_fake = self.spline_weight.abs().mean(-1)
    regularization_loss_activation = l1_fake.sum()
    p = l1_fake / regularization_loss_activation
    regularization_loss_entropy = -torch.sum(p * p.log())
    return (
        regularize_activation * regularization_loss_activation
        + regularize_entropy * regularization_loss_entropy
    )

class KAN(torch.nn.Module):
    def __init__(
        self,
        layers_hidden,
        grid_size=5,
        spline_order=3,
        scale_base=1.0,
        scale_spline=1.0,
        base_activation=torch.nn.SiLU,
        grid_eps=0.02,
        grid_range=[-1, 1],
    ):
        super(KAN, self).__init__()
        self.grid_size = grid_size
        self.spline_order = spline_order

        # 構建 KAN 的層
        self.layers = self.build_layers(
            layers_hidden, grid_size, spline_order, scale_base, scale_spline, base_activation, grid_eps,
            grid_range
        )

    def build_layers(self, layers_hidden, grid_size, spline_order, scale_base, scale_spline, base_activation,
        grid_eps,
        grid_range):
        layers = torch.nn.ModuleList()
        for in_features, out_features in zip(layers_hidden, layers_hidden[1:]):
            layers.append(
                KANLinear(
                    in_features,
                    out_features,
                    grid_size=grid_size,
                    spline_order=spline_order,
                    scale_base=scale_base,
                    scale_spline=scale_spline,
                    base_activation=base_activation,
                    grid_eps=grid_eps,
                    grid_range=grid_range,
                )
            )
        return layers

    def forward(self, x: torch.Tensor, update_grid=False):
        for layer in self.layers:
            if update_grid:
                layer.update_grid(x)
            x = layer(x)
        return x

    def regularization_loss(self, regularize_activation=1.0, regularize_entropy=1.0):
        return sum(
            layer.regularization_loss(regularize_activation, regularize_entropy)
            for layer in self.layers
        )

```

- 創建 Kolmogorov-Arnold Network 進行測試 · 資料集使用 MNIST 手寫數字辨識

```

from EfficientKAN import KAN

# Train on MNIST
import torch
import torch.nn as nn
import torch.optim as optim
import torchvision
import torchvision.transforms as transforms
from torch.utils.data import DataLoader
from tqdm import tqdm

# Load MNIST
transform = transforms.Compose(
    [transforms.ToTensor(), transforms.Normalize((0.5,), (0.5,))]
)
trainset = torchvision.datasets.MNIST(
    root="./data", train=True, download=True, transform=transform
)
valset = torchvision.datasets.MNIST(
    root="./data", train=False, download=True, transform=transform
)
trainloader = DataLoader(trainset, batch_size=64, shuffle=True)
valloader = DataLoader(valset, batch_size=64, shuffle=False)

# Define model
model = KAN([28 * 28, 64, 10])
device = torch.device("cuda" if torch.cuda.is_available() else "cpu")
model.to(device)
# Define optimizer
optimizer = optim.AdamW(model.parameters(), lr=1e-3, weight_decay=1e-4)
# Define learning rate scheduler
scheduler = optim.lr_scheduler.ExponentialLR(optimizer, gamma=0.8)

# Define loss
criterion = nn.CrossEntropyLoss()
for epoch in range(10):
    # Train
    model.train()
    with tqdm(trainloader) as pbar:
        for i, (images, labels) in enumerate(pbar):
            images = images.view(-1, 28 * 28).to(device)
            optimizer.zero_grad()
            output = model(images)
            loss = criterion(output, labels.to(device))
            loss.backward()
            optimizer.step()
            accuracy = (output.argmax(dim=1) == labels.to(device)).float().mean()
            pbar.set_postfix(loss=loss.item(), accuracy=accuracy.item(), lr=optimizer.param_groups[0]['lr'])

    # Validation
    model.eval()
    val_loss = 0
    val_accuracy = 0
    with torch.no_grad():
        for images, labels in valloader:
            images = images.view(-1, 28 * 28).to(device)
            output = model(images)
            val_loss += criterion(output, labels.to(device)).item()
            val_accuracy += (
                (output.argmax(dim=1) == labels.to(device)).float().mean().item()
            )
    val_loss /= len(valloader)
    val_accuracy /= len(valloader)

    # Update learning rate
    scheduler.step()

    print(
        f"Epoch {epoch + 1}, Val Loss: {val_loss}, Val Accuracy: {val_accuracy}"
    )

```

```
# Print model weights
print("Trained Model Weights:")

for i, layer in enumerate(model.layers):
    print(f"Layer {i + 1}:")
    print("Spline Weights:")
    print(layer.spline_weight)
    print("Base Weights:")
    print(layer.base_weight)
    print()

# Save model weights (need to create KAN instance then "torch.load")
torch.save(model.state_dict(), "kan_mnist_weights.pth")
# Save the entire model (just get with "torch.load")
torch.save(model, "kan_mnist_model.pth")
```

- Model 於 MNIST 之訓練結果

```
100%|██████████| 938/938 [00:40<00:00, 23.07it/s, accuracy=1, loss=0.031, lr=0.000134]
Epoch 10, Val Loss: 0.08577567627701677, Val Accuracy: 0.9750199044585988
```

- 創建 Kolmogorov-Arnold Network 進行測試 · 函數擬合簡易乘法 $a \times b$

```
import torch
import torch.nn as nn
from tqdm import tqdm

from EfficientKAN import KAN

def test_mul():
    kan = KAN([2, 3, 3, 1], base_activation=nn.Identity)
    optimizer = torch.optim.LBFGS(kan.parameters(), lr=0.001)

    with tqdm(range(200)) as pbar:
        for i in pbar:
            loss, reg_loss = None, None

            def closure():
                optimizer.zero_grad()
                x = torch.rand(1024, 2)
                y = kan(x, update_grid=(i % 20 == 0))
                assert y.shape == (1024, 1)
                nonlocal loss, reg_loss
                u = x[:, 0]
                v = x[:, 1]
                loss = nn.functional.mse_loss(y.squeeze(-1), u * v)
                reg_loss = kan.regularization_loss(1, 0)
                (loss + 1e-5 * reg_loss).backward()
                return loss + reg_loss

            optimizer.step(closure)
            pbar.set_postfix(mse_loss=loss.item(), reg_loss=reg_loss.item())

    for layer in kan.layers:
        print(layer.spline_weight)

    torch.save(kan, 'model/kan_multiple_model.pth')
    torch.save(kan.state_dict(), "model/kan_multiple_weights.pth")

# Test the trained model
test_model(kan)

def test_model(model):
    model.eval()
    with torch.no_grad():
        test_x = torch.rand(1024, 2)
```



```

test_y = model(test_x)
u = test_x[:, 0]
v = test_x[:, 1]
expected_y = u * v
test_loss = nn.functional.mse_loss(test_y.squeeze(-1), expected_y)
print(f"Test Loss: {test_loss.item():.4f}")

```

test_mul()

- Model 於函數擬合簡易乘法之訓練結果

```
100%|██████████| 200/200 [01:03<00:00, 3.13it/s, mse_loss=0.0938, reg_loss=9.12e-7]
```

訓練模型 Quantization 處理

Info

最基本的 Quantization 實現，使用 PyTorch 庫進行 INT8 Quantization 操作並保存模型。

- PyTorch INT8 Quantization 代碼實現

```

import torch
import torch.nn as nn
import torch.quantization

from EfficientKAN import KAN

def quantize_model(model_path, model_weights_path):
    # 加載模型架構
    model = torch.load(model_path)

    # 加載模型權重
    model.load_state_dict(torch.load(model_weights_path))

    model.eval()

    # 設置量化配置為INT8
    model.qconfig = torch.quantization.QConfig(
        activation=torch.quantization.MinMaxObserver.with_args(dtype=torch.qint8, quant_min=0, quant_max=255),
        weight=torch.quantization.PerChannelMinMaxObserver.with_args(dtype=torch.qint8, quant_min=-128,
quant_max=127)
    )

    # 準備模型進行量化
    model = torch.quantization.prepare(model, inplace=True)

    # 使用校準數據進行量化校準
    calibrate_model(model)

    # 轉換為量化模型
    model = torch.quantization.convert(model, inplace=True)

    # 保存量化後的模型
    torch.save(model, 'model/kan_multiple_model_quantized.pth')
    torch.save(model.state_dict(), "model/kan_multiple_weights_quantized.pth")

    # 測試量化後的模型
    test_model(model)

def calibrate_model(model):
    # 使用隨機數據進行校準
    with torch.no_grad():
        for _ in range(100):

```

```

        test_x = torch.rand(1024, 2)
        model(test_x)

def test_model(model):
    model.eval()
    with torch.no_grad():
        test_x = torch.rand(1024, 2)
        test_y = model(test_x)
        u = test_x[:, 0]
        v = test_x[:, 1]
        expected_y = u * v
        test_loss = nn.functional.mse_loss(test_y.squeeze(-1), expected_y)
        print(f"Test Loss: {test_loss.item():.4f}")

# 使用訓練好的模型路徑和權重文件路徑
model_path = 'model/kan_multiple_model.pth'
model_weights_path = 'model/kan_multiple_weights.pth'

quantize_model(model_path, model_weights_path)

```

The screenshot shows a VS Code editor with a project named 'KANPyTorch'. The file explorer on the left shows a directory structure with files like 'kan_mnist_model.pth', 'kan_mnist_weights.pth', 'kan_multiple_model.pth', 'kan_multiple_weights.pth', 'kan_multiple_weights_quantized.pth', 'EfficientKAN.py', 'quantKAN.py', 'quantMNIST.py', 'requirements.txt', 'testKAN.py', and 'testMNIST.py'. The main editor window shows the code for the `quantize_model` function. The function takes `model_path` and `model_weights_path` as arguments. It loads the model, sets the quantization config to INT8, and then quantizes the model using `torch.quantization.prepare` and `calibrate_model`. The output of the function is shown in the Run and Debug console, which displays 'Test Loss: 0.1243' and 'Process finished with exit code 0'.

```

def quantize_model(model_path, model_weights_path):
    model.eval()

    # 設置量化配置為INT8
    model.qconfig = torch.quantization.QConfig(
        activation=torch.quantization.MinMaxObserver.with_args(dtype=torch.qint8, quant_min=0, quant_max=127),
        weight=torch.quantization.PerChannelMinMaxObserver.with_args(dtype=torch.qint8, quant_min=-128, quant_max=127)
    )

    # 準備模型進行量化
    model = torch.quantization.prepare(model, inplace=True)

    # 使用校準數據進行量化校準
    calibrate_model(model)

    # 輸出校準後的模型和權重

```

Info

進一步將 Quantization 後的 Weights 導出成 CSV，提供給後續推論調用進行使用。

Warning

發現導出的 CSV 結果依舊是浮點數，需要再次確認為何是 CSV 是吃到原始的 Weights 而非 Quantization 後的 Weights。

Check

在 PyTorch 中進行量化時，模型的權重並不會直接在 `state_dict` 中顯示為 INT8。這是因為 PyTorch 量化模型的權重會被存儲為浮點數，但在推理時會被視為 INT8。具體來說，量化過程會引入 `FakeQuantize` 模塊來模擬 INT8 行為，但權重仍然以浮點數形式存在。

- PyTorch INT8 Quantization 含 CSV 權重導出

```

import os

import numpy as np
import torch
import torch.nn as nn
import torch.quantization

def quantize_model(model_path, model_weights_path):
    # 加載模型架構
    model = torch.load(model_path)

    # 加載模型權重
    model.load_state_dict(torch.load(model_weights_path))

    model.eval()

    # 設置量化配置為INT8
    model.qconfig = torch.quantization.default_qconfig

    # 準備模型進行量化
    torch.quantization.prepare(model, inplace=False)

    # 使用校準數據進行量化校準
    calibrate_model(model)

    # 轉換為量化模型
    torch.quantization.convert(model, inplace=False)

    # 保存量化後的模型
    torch.save(model.state_dict(), "model/kan_multiple_weights_quantized.pth")
    torch.save(model, 'model/kan_multiple_model_quantized.pth')

    # 導出量化後的權重
    export_weights_to_csv(model, "model/quantized_weights")

    # print(model.state_dict())

    # 測試量化後的模型
    test_model(model)

def calibrate_model(model):
    # 使用隨機數據進行校準
    with torch.no_grad():
        for _ in range(100):
            test_x = torch.rand(1024, 2)
            model(test_x)

def test_model(model):
    model.eval()
    with torch.no_grad():
        test_x = torch.rand(1024, 2)
        test_y = model(test_x)
        u = test_x[:, 0]
        v = test_x[:, 1]
        expected_y = u * v
        test_loss = nn.functional.mse_loss(test_y.squeeze(-1), expected_y)
        print(f"Test Loss: {test_loss.item():.4f}")

def export_weights_to_csv(model, folder_path):
    if not os.path.exists(folder_path):
        os.makedirs(folder_path)

    # 遍歷模型中的每一層，並將權重存儲在單獨的 CSV 文件中
    for name, param in model.named_parameters():
        if param.requires_grad:
            weight_array = param.detach().cpu().numpy()

```

```

file_path = os.path.join(folder_path, f"{name}.csv")
np.savetxt(file_path, weight_array.flatten(), delimiter=",")
print(f"Weights of {name} exported to {file_path}")

```

使用訓練好的模型路徑和權重文件路徑

```

model_path = 'model/kan_multiple_model.pth'
model_weights_path = 'model/kan_multiple_weights.pth'

```

```
quantize_model(model_path, model_weights_path)
```

```

1 usage new *
10 def quantize_model(model_path, model_weights_path):
11     # 加載模型架構
12     model = torch.load(model_path)
13
14     # 加載模型權重
15     model.load_state_dict(torch.load(model_weights_path))

```

Run console output:

```

C:\Anaconda\envs\KANPyTorch\python.exe C:\Users\toby0\Documents\GitHub\Kolmogorov-Arnold-Network-Digital-Design\KANPyTorch\quan
Weights of layers.0.base_weight exported to model/quantized_weights\layers.0.base_weight.csv
Weights of layers.0.spline_weight exported to model/quantized_weights\layers.0.spline_weight.csv
Weights of layers.0.spline_scaler exported to model/quantized_weights\layers.0.spline_scaler.csv
Weights of layers.1.base_weight exported to model/quantized_weights\layers.1.base_weight.csv
Weights of layers.1.spline_weight exported to model/quantized_weights\layers.1.spline_weight.csv
Weights of layers.1.spline_scaler exported to model/quantized_weights\layers.1.spline_scaler.csv
Weights of layers.2.base_weight exported to model/quantized_weights\layers.2.base_weight.csv
Weights of layers.2.spline_weight exported to model/quantized_weights\layers.2.spline_weight.csv
Weights of layers.2.spline_scaler exported to model/quantized_weights\layers.2.spline_scaler.csv
Test Loss: 0.1275

Process finished with exit code 0

```

```

1 4.569392800331115723e-01
2 -4.573425054550170898e-01
3 6.814478039741516113e-01
4 -6.695145964622497559e-01
5 9.034241735935211182e-02
6 6.441026926040649414e-01
7

```

Run console output:

```

Weights of layers.1.spline_weight exported to model/quantized_weights\layers.1.spline_weight.csv
Weights of layers.1.spline_scaler exported to model/quantized_weights\layers.1.spline_scaler.csv
Weights of layers.2.base_weight exported to model/quantized_weights\layers.2.base_weight.csv
Weights of layers.2.spline_weight exported to model/quantized_weights\layers.2.spline_weight.csv

```

Info

由於 PyTorch Quantization 的性質，改為使用手動實現 Quantization 工具，方法採用 Symmetric Quantization。

Summary

Symmetric Quantization 是指將數值範圍對稱地映射到量化級別。具體來說，就是把模型參數或激活值的浮點數範圍對稱地映射到固定的整數範圍，使得量化後的數值在正負兩個方向上具有相同的動態範圍。

1. 對稱映射：浮點數的正負最大值絕對值相等，映射到整數範圍時也是對稱的。例如，如果浮點數的範圍是 $[-a, a]$ ，那麼在 INT8 量化後的範圍就是 $[-127, 127]$ （因為 INT8 的範圍是 -128 到 127，但通常會保留一個值作為零點）。
2. 縮放因子 (scaling factor)：這個對稱的範圍由一個縮放因子來確定，縮放因子是浮點數最大絕對值與整數最大值之間的比例。公式如下：

$$\text{textScalingFactor} = \frac{\text{Max Absolute Float Value}}{\text{Max Absolute Integer Value}}$$

3. 零點 (zero point)：對稱量化的零點通常是 0，這樣可以確保零值在量化和反量化後不會發生偏移。
4. 簡化運算：由於對稱量化的特性，運算過程中可以避免某些複雜的偏移和對齊操作，從而提升計算效率。

Example

假設有一組浮點數值範圍 $[-6, 6]$ ，我們希望將它量化到 INT8 範圍 $[-127, 127]$ 。這時的縮放因子就是：

$$\text{textScalingFactor} = \frac{6}{127} \approx 0.0472$$

任何一個浮點數 x 經過量化後的整數值就是：

$$\text{textQuantizedValue} = \text{round}(x / \text{Scaling Factor})$$

例如，浮點數 3 經過量化後的整數值是：

$$\text{textQuantizedValue} = \text{round}(3 / 0.0472) \approx 64$$

• 手動實現 Quantization

```
import os

import numpy as np
import torch
import torch.nn as nn
import torch.quantization

def quantize_tensor(tensor, num_bits=8):
    qmin = 0.
    qmax = 2. ** num_bits - 1.

    min_val, max_val = tensor.min(), tensor.max()
    scale = (max_val - min_val) / (qmax - qmin)
    zero_point = qmin - min_val / scale

    zero_point = int(zero_point)
    q_tensor = (tensor / scale + zero_point).round().clamp(qmin, qmax)

    return q_tensor, scale, zero_point

def dequantize_tensor(q_tensor, scale, zero_point):
    return scale * (q_tensor - zero_point)

def quantize_model(model_path, model_weights_path):
    # 加載模型架構
    model = torch.load(model_path)

    # 加載模型權重
    model.load_state_dict(torch.load(model_weights_path))

    model.eval()

    # 手動量化模型中的權重
```

```

for name, param in model.named_parameters():
    if param.requires_grad:
        q_param, scale, zero_point = quantize_tensor(param.data)
        param.data = dequantize_tensor(q_param, scale, zero_point)
        param.q_scale = scale
        param.q_zero_point = zero_point

# 保存量化後的模型
torch.save(model.state_dict(), "model/kan_multiple_weights_quantized.pth")
torch.save(model, 'model/kan_multiple_model_quantized.pth')

# 導出量化後的權重
export_weights_to_csv(model, "model/quantized_weights")

# 測試量化後的模型
test_model(model)

def calibrate_model(model):
    # 使用隨機數據進行校準
    with torch.no_grad():
        for _ in range(100):
            test_x = torch.rand(1024, 2)
            model(test_x)

def test_model(model):
    model.eval()
    with torch.no_grad():
        test_x = torch.rand(1024, 2)
        test_y = model(test_x)
        u = test_x[:, 0]
        v = test_x[:, 1]
        expected_y = u * v
        test_loss = nn.functional.mse_loss(test_y.squeeze(-1), expected_y)
        print(f"Test Loss: {test_loss.item():.4f}")

def export_weights_to_csv(model, folder_path):
    if not os.path.exists(folder_path):
        os.makedirs(folder_path)

    # 遍歷模型中的每一層，並將權重存儲在單獨的 CSV 文件中
    for name, param in model.named_parameters():
        if param.requires_grad:
            weight_array = param.detach().cpu().numpy()
            scale = param.q_scale
            zero_point = param.q_zero_point
            q_weights = (weight_array / scale + zero_point).round()
            file_path = os.path.join(folder_path, f"{name}.csv")
            np.savetxt(file_path, q_weights.flatten(), delimiter=",")
            print(f"Weights of {name} exported to {file_path}")

# 使用訓練好的模型路徑和權重文件路徑
model_path = 'model/kan_multiple_model.pth'
model_weights_path = 'model/kan_multiple_weights.pth'

quantize_model(model_path, model_weights_path)

```

```
def export_weights_to_csv(model, folder_path):
    scale = param.q_scale
    zero_point = param.q_zero_point
    q_weights = (weight_array / scale + zero_point).round()
    file_path = os.path.join(folder_path, f"{name}.csv")
    np.savetxt(file_path, q_weights.flatten(), delimiter=",")
    print(f"Weights of {name} exported to {file_path}")
```

Run fixedEKAN

C:\Anaconda\envs\KANPyTorch\python.exe C:\Users\toby0\Documents\GitHub\Kolmogorov-Arnold-Network-Digital-Design\KANPyTorch\fixe

Weights of layers.0.base_weight exported to model/quantized_weights\layers.0.base_weight.csv
Weights of layers.0.spline_weight exported to model/quantized_weights\layers.0.spline_weight.csv
Weights of layers.0.spline_scaler exported to model/quantized_weights\layers.0.spline_scaler.csv
Weights of layers.1.base_weight exported to model/quantized_weights\layers.1.base_weight.csv
Weights of layers.1.spline_weight exported to model/quantized_weights\layers.1.spline_weight.csv
Weights of layers.1.spline_scaler exported to model/quantized_weights\layers.1.spline_scaler.csv
Weights of layers.2.base_weight exported to model/quantized_weights\layers.2.base_weight.csv
Weights of layers.2.spline_weight exported to model/quantized_weights\layers.2.spline_weight.csv
Weights of layers.2.spline_scaler exported to model/quantized_weights\layers.2.spline_scaler.csv
Test Loss: 0.1259
Process finished with exit code 0

```
1 2.5500000000000000e+02
2 1.1400000000000000e+02
3 2.4900000000000000e+02
4 0.0000000000000000e+00
5 2.5400000000000000e+02
6 2.2000000000000000e+02
7
```

Run fixedEKAN

C:\Anaconda\envs\KANPyTorch\python.exe C:\Users\toby0\Documents\GitHub\Kolmogorov-Arnold-Network-Digital-Design\KANPyTorch\fixe

Weights of layers.0.base_weight exported to model/quantized_weights\layers.0.base_weight.csv
Weights of layers.0.spline_weight exported to model/quantized_weights\layers.0.spline_weight.csv
Weights of layers.0.spline_scaler exported to model/quantized_weights\layers.0.spline_scaler.csv

Info

將 Quantization 後的 Weights 進一步處理為二進制輸出 (同時自定義 Quantization 寬度)

- 二進制輸出及自定義量化寬度

```
import os
import numpy as np
import torch
import torch.nn as nn
import torch.quantization

def quantize_tensor(tensor, num_bits):
    qmin = 0.
```

```

qmax = 2. ** num_bits - 1.

min_val, max_val = tensor.min(), tensor.max()
scale = (max_val - min_val) / (qmax - qmin)
zero_point = qmin - min_val / scale

zero_point = int(zero_point)
q_tensor = (tensor / scale + zero_point).round().clamp(qmin, qmax)

return q_tensor, scale, zero_point

def dequantize_tensor(q_tensor, scale, zero_point):
    return scale * (q_tensor - zero_point)

def quantize_model(model_path, model_weights_path, num_bits):
    # 加載模型架構
    model = torch.load(model_path)

    # 加載模型權重
    model.load_state_dict(torch.load(model_weights_path))

    model.eval()

    # 手動量化模型中的權重
    for name, param in model.named_parameters():
        if param.requires_grad:
            q_param, scale, zero_point = quantize_tensor(param.data, num_bits)
            param.data = dequantize_tensor(q_param, scale, zero_point)
            param.q_scale = scale
            param.q_zero_point = zero_point

    # 保存量化後的模型
    torch.save(model.state_dict(), "model/kan_multiple_weights_quantized.pth")
    torch.save(model, 'model/kan_multiple_model_quantized.pth')

    # 導出量化後的權重
    export_weights_to_csv(model, "model/quantized_weights", num_bits)

    # 測試量化後的模型
    test_model(model)

def calibrate_model(model):
    # 使用隨機數據進行校準
    with torch.no_grad():
        for _ in range(100):
            test_x = torch.rand(1024, 2)
            model(test_x)

def test_model(model):
    model.eval()
    with torch.no_grad():
        test_x = torch.rand(1024, 2)
        test_y = model(test_x)
        u = test_x[:, 0]
        v = test_x[:, 1]
        expected_y = u * v
        test_loss = nn.functional.mse_loss(test_y.squeeze(-1), expected_y)
        print(f"Test Loss: {test_loss.item():.4f}")

def export_weights_to_csv(model, folder_path, num_bits):
    if not os.path.exists(folder_path):
        os.makedirs(folder_path)

    # 遍歷模型中的每一層，並將權重存儲在單獨的 CSV 文件中
    for name, param in model.named_parameters():
        if param.requires_grad:

```



```

weight_array = param.detach().cpu().numpy()
scale = param.q_scale
zero_point = param.q_zero_point
q_weights = (weight_array / scale + zero_point).round()
file_path = os.path.join(folder_path, f"{name}.csv")
np.savetxt(file_path, q_weights.flatten(), delimiter=",")
print(f"Weights of {name} exported to {file_path}")

def read_convert_and_write_binary(folder_path, num_bits):
    # 遍歷文件夾中的所有CSV文件
    for file_name in os.listdir(folder_path):
        if file_name.endswith(".csv"):
            file_path = os.path.join(folder_path, file_name)
            # 讀取CSV文件
            data = np.loadtxt(file_path, delimiter=",")
            # 將數據轉換為二進制格式
            binary_data = np.vectorize(np.binary_repr)(data.astype(int), width=num_bits)
            # 將二進制數據寫回CSV文件
            with open(file_path, 'w') as f:
                for binary_value in binary_data:
                    f.write(f"{binary_value}\n")
            print(f"Binary values written to {file_name}")

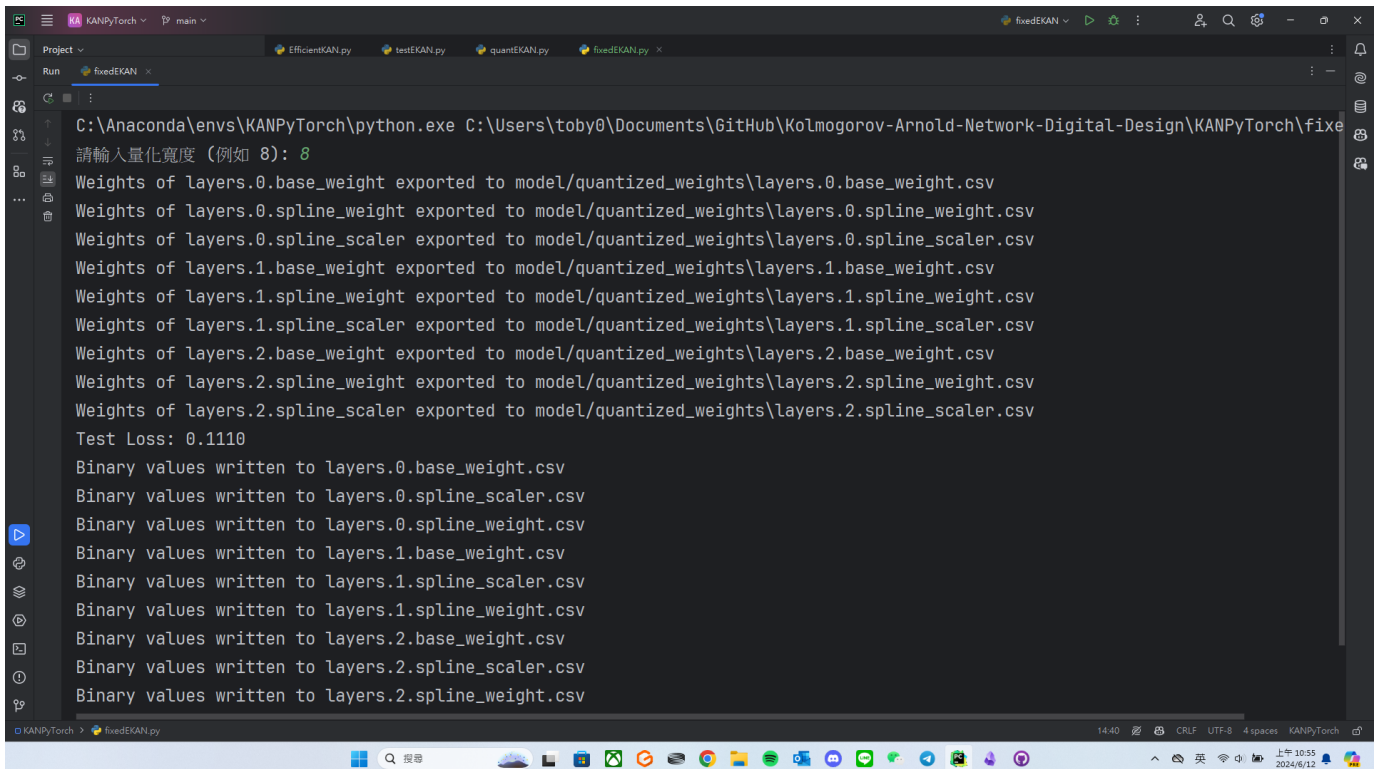
if __name__ == "__main__":
    # 從終端獲取量化寬度
    num_bits = int(input("請輸入量化寬度 (例如 8): "))

    # 使用訓練好的模型路徑和權重文件路徑
    model_path = 'model/kan_multiple_model.pth'
    model_weights_path = 'model/kan_multiple_weights.pth'

    quantize_model(model_path, model_weights_path, num_bits)

    # 調用函數，讀取並轉換文件夾中的CSV文件
    folder_path = "model/quantized_weights"
    read_convert_and_write_binary(folder_path, num_bits)

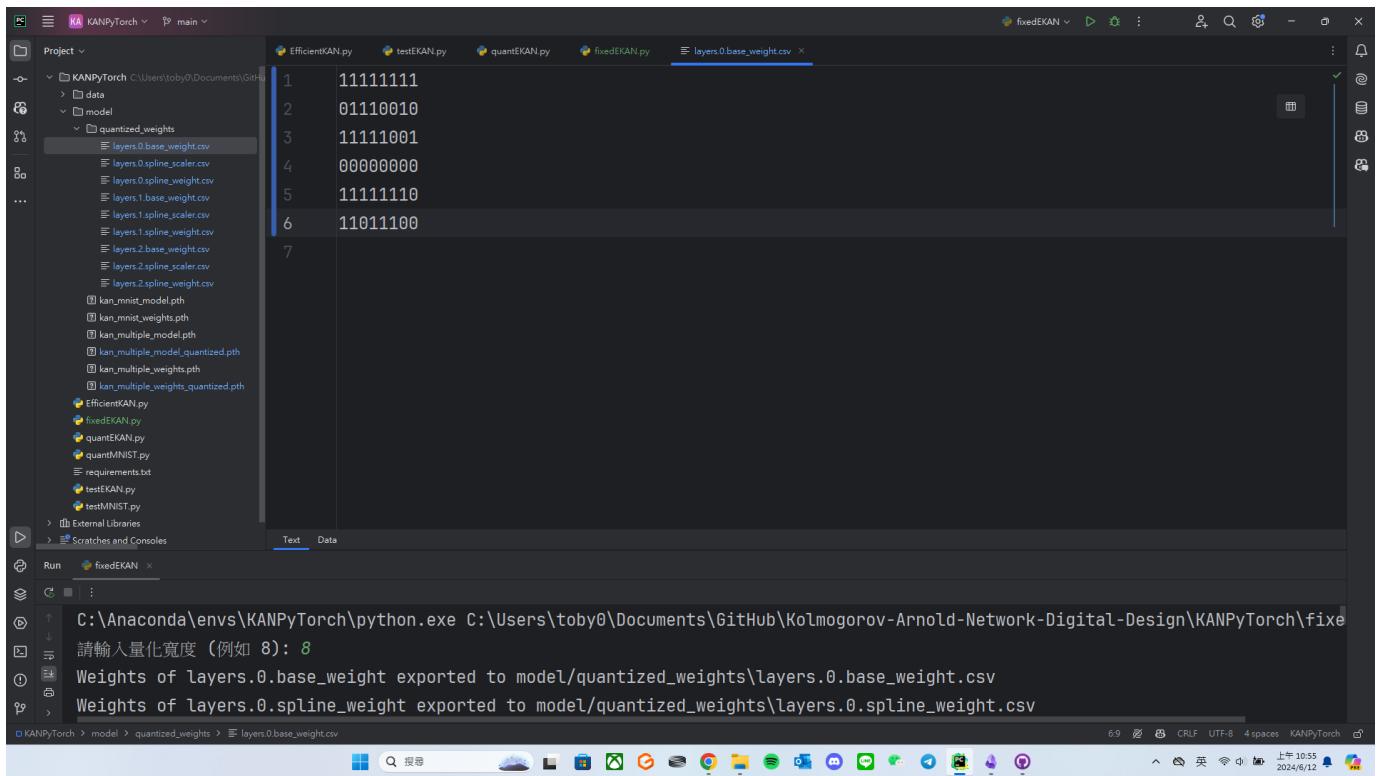
```



```

C:\Anaconda\envs\KANPyTorch\python.exe C:\Users\toby0\Documents\GitHub\Kolmogorov-Arnold-Network-Digital-Design\KANPyTorch\fixe
請輸入量化寬度 (例如 8): 8
Weights of layers.0.base_weight exported to model/quantized_weights\layers.0.base_weight.csv
Weights of layers.0.spline_weight exported to model/quantized_weights\layers.0.spline_weight.csv
Weights of layers.0.spline_scaler exported to model/quantized_weights\layers.0.spline_scaler.csv
Weights of layers.1.base_weight exported to model/quantized_weights\layers.1.base_weight.csv
Weights of layers.1.spline_weight exported to model/quantized_weights\layers.1.spline_weight.csv
Weights of layers.1.spline_scaler exported to model/quantized_weights\layers.1.spline_scaler.csv
Weights of layers.2.base_weight exported to model/quantized_weights\layers.2.base_weight.csv
Weights of layers.2.spline_weight exported to model/quantized_weights\layers.2.spline_weight.csv
Weights of layers.2.spline_scaler exported to model/quantized_weights\layers.2.spline_scaler.csv
Test Loss: 0.1110
Binary values written to layers.0.base_weight.csv
Binary values written to layers.0.spline_scaler.csv
Binary values written to layers.0.spline_weight.csv
Binary values written to layers.1.base_weight.csv
Binary values written to layers.1.spline_scaler.csv
Binary values written to layers.1.spline_weight.csv
Binary values written to layers.2.base_weight.csv
Binary values written to layers.2.spline_scaler.csv
Binary values written to layers.2.spline_weight.csv

```



方法論合成 Grafcet 控制器電路

Success

更換測試資料及 Network 設計以求可以將電路設計容納進去 (學習函數擬合簡易乘法 · KAN 的架構為 [2, 3, 3, 1])。

Tip

Verilog 僅供模型推論使用。

- Model to Verilog Generator 實現

```
import os

def read_quantized_weights(folder_path):
    weights = {}
    for file_name in os.listdir(folder_path):
        if file_name.endswith(".csv"):
            layer_name = file_name.replace(".csv", "").replace(".", "_")
            file_path = os.path.join(folder_path, file_name)
            with open(file_path, 'r') as f:
                binary_data = [line.strip() for line in f]
                weights[layer_name] = binary_data
    return weights

def generate_verilog(weights, num_bits=8):
    verilog_code = """module KAN(
    input wire clk,    input wire rst,    input wire [31:0] x1,    input wire [31:0] x2,    output wire [31:0]
y);

// Intermediate signals
wire [31:0] layer0_out_0;
wire [31:0] layer0_out_1;
wire [31:0] layer0_out_2;
wire [31:0] layer1_out_0;
wire [31:0] layer1_out_1;
```

```

wire [31:0] layer1_out_2;
wire [31:0] layer2_out;

"""

# 宣告所有權重變量
for layer_name, binary_data in weights.items():
    for i, binary_line in enumerate(binary_data):
        verilog_code += f"reg [{num_bits} - 1]:0 {layer_name}_{i};\n"

verilog_code += "\ninitial begin\n"
# 初始化所有權重變量
for layer_name, binary_data in weights.items():
    for i, binary_line in enumerate(binary_data):
        verilog_code += f"    {layer_name}_{i} = {num_bits}'b{binary_line};\n"
verilog_code += "end\n\n"

verilog_code += """
// Layer 0: Input to hidden
assign layer0_out_0 = x1 * layers_0_base_weight_0 + x2 * layers_0_base_weight_1;
assign layer0_out_1 = x1 * layers_0_base_weight_2 + x2 * layers_0_base_weight_3;
assign layer0_out_2 = x1 * layers_0_base_weight_4 + x2 * layers_0_base_weight_5;

// Layer 1: Hidden to hidden
assign layer1_out_0 = layer0_out_0 * layers_1_base_weight_0 + layer0_out_1 * layers_1_base_weight_1 +
layer0_out_2 * layers_1_base_weight_2;
assign layer1_out_1 = layer0_out_0 * layers_1_base_weight_3 + layer0_out_1 * layers_1_base_weight_4 +
layer0_out_2 * layers_1_base_weight_5;
assign layer1_out_2 = layer0_out_0 * layers_1_base_weight_6 + layer0_out_1 * layers_1_base_weight_7 +
layer0_out_2 * layers_1_base_weight_8;

// Layer 2: Hidden to output
assign layer2_out = layer1_out_0 * layers_2_base_weight_0 + layer1_out_1 * layers_2_base_weight_1 + layer1_out_2
* layers_2_base_weight_2;

assign y = layer2_out;

endmodule
"""

return verilog_code

if __name__ == "__main__":
    folder_path = "model/quantized_weights"
    num_bits = 8 # 可以根據實際需要調整量化位數
    weights = read_quantized_weights(folder_path)
    verilog_code = generate_verilog(weights, num_bits)

    with open("logic/kan_model.v", "w") as f:
        f.write(verilog_code)
    print("Verilog code generated and saved as kan_model.v")

```

⚠ Caution

「Deprecated Version」 MNIST 版本之 Reference

- KANLayer 實現 (KANLayer.v)

```

module KANLayer #(
    parameter IN_FEATURES = 784,
    parameter OUT_FEATURES = 64,
    parameter SCALE = 256, // Quantization scale factor
    parameter BASE_WEIGHT_FILE = "C:/intelFPGA_lite/18.1/KAN/base_weight_layer_0.txt",
    parameter SPLINE_WEIGHT_FILE = "C:/intelFPGA_lite/18.1/KAN/spline_weight_layer_0.txt"
)(
    input wire clk,
    input wire reset,
    input wire [7:0] in_data [0:IN_FEATURES-1], // Input data
    output reg [7:0] out_data [0:OUT_FEATURES-1] // Output data

```

```

);
// Weights stored in on-chip memory (BRAM)
reg signed [15:0] base_weights [0:OUT_FEATURES*IN_FEATURES-1];
reg signed [15:0] spline_weights [0:OUT_FEATURES*IN_FEATURES-1];

// Load weights from memory (initialization)
initial begin
    $readmemh(BASE_WEIGHT_FILE, base_weights);
    $readmemh(SPLINE_WEIGHT_FILE, spline_weights);
end

// Output registers
reg signed [31:0] base_output [0:OUT_FEATURES-1];
reg signed [31:0] spline_output [0:OUT_FEATURES-1];
reg signed [31:0] total_output [0:OUT_FEATURES-1];

integer i, j;

// Forward pass
always @(posedge clk or posedge reset) begin
    if (reset) begin
        for (i = 0; i < OUT_FEATURES; i = i + 1) begin
            base_output[i] ≤ 0;
            spline_output[i] ≤ 0;
            total_output[i] ≤ 0;
        end
    end else begin
        for (i = 0; i < OUT_FEATURES; i = i + 1) begin
            base_output[i] ≤ 0;
            spline_output[i] ≤ 0;
            for (j = 0; j < IN_FEATURES; j = j + 1) begin
                base_output[i] ≤ base_output[i] + in_data[j] * base_weights[i*IN_FEATURES + j];
                spline_output[i] ≤ spline_output[i] + in_data[j] * spline_weights[i*IN_FEATURES + j];
            end
            total_output[i] ≤ (base_output[i] + spline_output[i]) / SCALE; // Combine and scale the outputs
            out_data[i] ≤ total_output[i][15:8]; // Convert to 8-bit output
        end
    end
end
endmodule

```

ChatGPT 合成 Grafcet Datapath 電路

✔ Success

更換測試資料及 **Network** 設計以求可以將電路設計容納進去 (學習函數擬合簡易乘法 · KAN 的架構為 [2, 3, 3, 1])。

💡 Tip

Verilog 僅供模型推論使用。

- 完整 **Network** 實現 (KAN.v)

```

module KAN(
    input wire clk,
    input wire rst,
    input wire [31:0] x1,
    input wire [31:0] x2,
    output wire [31:0] y
);

// Intermediate signals
wire [31:0] layer0_out_0;
wire [31:0] layer0_out_1;
wire [31:0] layer0_out_2;

```

```
wire [31:0] layer1_out_0;
wire [31:0] layer1_out_1;
wire [31:0] layer1_out_2;
wire [31:0] layer2_out;

reg [7:0] layers_0_base_weight_0;
reg [7:0] layers_0_base_weight_1;
reg [7:0] layers_0_base_weight_2;
reg [7:0] layers_0_base_weight_3;
reg [7:0] layers_0_base_weight_4;
reg [7:0] layers_0_base_weight_5;
reg [7:0] layers_0_spline_scaler_0;
reg [7:0] layers_0_spline_scaler_1;
reg [7:0] layers_0_spline_scaler_2;
reg [7:0] layers_0_spline_scaler_3;
reg [7:0] layers_0_spline_scaler_4;
reg [7:0] layers_0_spline_scaler_5;
reg [7:0] layers_0_spline_weight_0;
reg [7:0] layers_0_spline_weight_1;
reg [7:0] layers_0_spline_weight_2;
reg [7:0] layers_0_spline_weight_3;
reg [7:0] layers_0_spline_weight_4;
reg [7:0] layers_0_spline_weight_5;
reg [7:0] layers_0_spline_weight_6;
reg [7:0] layers_0_spline_weight_7;
reg [7:0] layers_0_spline_weight_8;
reg [7:0] layers_0_spline_weight_9;
reg [7:0] layers_0_spline_weight_10;
reg [7:0] layers_0_spline_weight_11;
reg [7:0] layers_0_spline_weight_12;
reg [7:0] layers_0_spline_weight_13;
reg [7:0] layers_0_spline_weight_14;
reg [7:0] layers_0_spline_weight_15;
reg [7:0] layers_0_spline_weight_16;
reg [7:0] layers_0_spline_weight_17;
reg [7:0] layers_0_spline_weight_18;
reg [7:0] layers_0_spline_weight_19;
reg [7:0] layers_0_spline_weight_20;
reg [7:0] layers_0_spline_weight_21;
reg [7:0] layers_0_spline_weight_22;
reg [7:0] layers_0_spline_weight_23;
reg [7:0] layers_0_spline_weight_24;
reg [7:0] layers_0_spline_weight_25;
reg [7:0] layers_0_spline_weight_26;
reg [7:0] layers_0_spline_weight_27;
reg [7:0] layers_0_spline_weight_28;
reg [7:0] layers_0_spline_weight_29;
reg [7:0] layers_0_spline_weight_30;
reg [7:0] layers_0_spline_weight_31;
reg [7:0] layers_0_spline_weight_32;
reg [7:0] layers_0_spline_weight_33;
reg [7:0] layers_0_spline_weight_34;
reg [7:0] layers_0_spline_weight_35;
reg [7:0] layers_0_spline_weight_36;
reg [7:0] layers_0_spline_weight_37;
reg [7:0] layers_0_spline_weight_38;
reg [7:0] layers_0_spline_weight_39;
reg [7:0] layers_0_spline_weight_40;
reg [7:0] layers_0_spline_weight_41;
reg [7:0] layers_0_spline_weight_42;
reg [7:0] layers_0_spline_weight_43;
reg [7:0] layers_0_spline_weight_44;
reg [7:0] layers_0_spline_weight_45;
reg [7:0] layers_0_spline_weight_46;
reg [7:0] layers_0_spline_weight_47;
reg [7:0] layers_1_base_weight_0;
reg [7:0] layers_1_base_weight_1;
reg [7:0] layers_1_base_weight_2;
reg [7:0] layers_1_base_weight_3;
reg [7:0] layers_1_base_weight_4;
reg [7:0] layers_1_base_weight_5;
```

[illegible]

```
reg [7:0] layers_1_spline_weight_59;
reg [7:0] layers_1_spline_weight_60;
reg [7:0] layers_1_spline_weight_61;
reg [7:0] layers_1_spline_weight_62;
reg [7:0] layers_1_spline_weight_63;
reg [7:0] layers_1_spline_weight_64;
reg [7:0] layers_1_spline_weight_65;
reg [7:0] layers_1_spline_weight_66;
reg [7:0] layers_1_spline_weight_67;
reg [7:0] layers_1_spline_weight_68;
reg [7:0] layers_1_spline_weight_69;
reg [7:0] layers_1_spline_weight_70;
reg [7:0] layers_1_spline_weight_71;
reg [7:0] layers_2_base_weight_0;
reg [7:0] layers_2_base_weight_1;
reg [7:0] layers_2_base_weight_2;
reg [7:0] layers_2_spline_scaler_0;
reg [7:0] layers_2_spline_scaler_1;
reg [7:0] layers_2_spline_scaler_2;
reg [7:0] layers_2_spline_weight_0;
reg [7:0] layers_2_spline_weight_1;
reg [7:0] layers_2_spline_weight_2;
reg [7:0] layers_2_spline_weight_3;
reg [7:0] layers_2_spline_weight_4;
reg [7:0] layers_2_spline_weight_5;
reg [7:0] layers_2_spline_weight_6;
reg [7:0] layers_2_spline_weight_7;
reg [7:0] layers_2_spline_weight_8;
reg [7:0] layers_2_spline_weight_9;
reg [7:0] layers_2_spline_weight_10;
reg [7:0] layers_2_spline_weight_11;
reg [7:0] layers_2_spline_weight_12;
reg [7:0] layers_2_spline_weight_13;
reg [7:0] layers_2_spline_weight_14;
reg [7:0] layers_2_spline_weight_15;
reg [7:0] layers_2_spline_weight_16;
reg [7:0] layers_2_spline_weight_17;
reg [7:0] layers_2_spline_weight_18;
reg [7:0] layers_2_spline_weight_19;
reg [7:0] layers_2_spline_weight_20;
reg [7:0] layers_2_spline_weight_21;
reg [7:0] layers_2_spline_weight_22;
reg [7:0] layers_2_spline_weight_23;
```

initial begin

```
    layers_0_base_weight_0 = 8'b11111111;
    layers_0_base_weight_1 = 8'b011110010;
    layers_0_base_weight_2 = 8'b111111001;
    layers_0_base_weight_3 = 8'b000000000;
    layers_0_base_weight_4 = 8'b111111110;
    layers_0_base_weight_5 = 8'b110111100;
    layers_0_spline_scaler_0 = 8'b000000000;
    layers_0_spline_scaler_1 = 8'b10010000;
    layers_0_spline_scaler_2 = 8'b10111000;
    layers_0_spline_scaler_3 = 8'b11100101;
    layers_0_spline_scaler_4 = 8'b01110111;
    layers_0_spline_scaler_5 = 8'b11111111;
    layers_0_spline_weight_0 = 8'b10111001;
    layers_0_spline_weight_1 = 8'b11000000;
    layers_0_spline_weight_2 = 8'b11000100;
    layers_0_spline_weight_3 = 8'b10011110;
    layers_0_spline_weight_4 = 8'b11101011;
    layers_0_spline_weight_5 = 8'b11111110;
    layers_0_spline_weight_6 = 8'b01101010;
    layers_0_spline_weight_7 = 8'b10101110;
    layers_0_spline_weight_8 = 8'b10111000;
    layers_0_spline_weight_9 = 8'b10111001;
    layers_0_spline_weight_10 = 8'b10111010;
    layers_0_spline_weight_11 = 8'b10111010;
    layers_0_spline_weight_12 = 8'b10110100;
    layers_0_spline_weight_13 = 8'b10111010;
```

```
layers_0_spline_weight_14 = 8'b10110111;
layers_0_spline_weight_15 = 8'b10110111;
layers_0_spline_weight_16 = 8'b10111000;
layers_0_spline_weight_17 = 8'b10111010;
layers_0_spline_weight_18 = 8'b10111100;
layers_0_spline_weight_19 = 8'b10110100;
layers_0_spline_weight_20 = 8'b10110010;
layers_0_spline_weight_21 = 8'b10101010;
layers_0_spline_weight_22 = 8'b10100101;
layers_0_spline_weight_23 = 8'b10110110;
layers_0_spline_weight_24 = 8'b10111000;
layers_0_spline_weight_25 = 8'b10111001;
layers_0_spline_weight_26 = 8'b10110101;
layers_0_spline_weight_27 = 8'b10101111;
layers_0_spline_weight_28 = 8'b10010111;
layers_0_spline_weight_29 = 8'b10011001;
layers_0_spline_weight_30 = 8'b10100001;
layers_0_spline_weight_31 = 8'b10110011;
layers_0_spline_weight_32 = 8'b10111000;
layers_0_spline_weight_33 = 8'b10110110;
layers_0_spline_weight_34 = 8'b10111001;
layers_0_spline_weight_35 = 8'b11010101;
layers_0_spline_weight_36 = 8'b11101010;
layers_0_spline_weight_37 = 8'b11111110;
layers_0_spline_weight_38 = 8'b11110000;
layers_0_spline_weight_39 = 8'b10111101;
layers_0_spline_weight_40 = 8'b10111000;
layers_0_spline_weight_41 = 8'b10111011;
layers_0_spline_weight_42 = 8'b10101010;
layers_0_spline_weight_43 = 8'b10000001;
layers_0_spline_weight_44 = 8'b00101110;
layers_0_spline_weight_45 = 8'b00000000;
layers_0_spline_weight_46 = 8'b01000110;
layers_0_spline_weight_47 = 8'b10101010;
layers_1_base_weight_0 = 8'b10101111;
layers_1_base_weight_1 = 8'b11100110;
layers_1_base_weight_2 = 8'b10111110;
layers_1_base_weight_3 = 8'b00101001;
layers_1_base_weight_4 = 8'b00010000;
layers_1_base_weight_5 = 8'b01101101;
layers_1_base_weight_6 = 8'b11111111;
layers_1_base_weight_7 = 8'b00000010;
layers_1_base_weight_8 = 8'b00000000;
layers_1_spline_scaler_0 = 8'b10011001;
layers_1_spline_scaler_1 = 8'b01111011;
layers_1_spline_scaler_2 = 8'b11101000;
layers_1_spline_scaler_3 = 8'b11000000;
layers_1_spline_scaler_4 = 8'b11111110;
layers_1_spline_scaler_5 = 8'b10001100;
layers_1_spline_scaler_6 = 8'b10110011;
layers_1_spline_scaler_7 = 8'b01000011;
layers_1_spline_scaler_8 = 8'b00000000;
layers_1_spline_weight_0 = 8'b01111001;
layers_1_spline_weight_1 = 8'b01110101;
layers_1_spline_weight_2 = 8'b01101101;
layers_1_spline_weight_3 = 8'b10000011;
layers_1_spline_weight_4 = 8'b01110011;
layers_1_spline_weight_5 = 8'b01100100;
layers_1_spline_weight_6 = 8'b10100010;
layers_1_spline_weight_7 = 8'b10000010;
layers_1_spline_weight_8 = 8'b01111001;
layers_1_spline_weight_9 = 8'b01111010;
layers_1_spline_weight_10 = 8'b01111010;
layers_1_spline_weight_11 = 8'b01110101;
layers_1_spline_weight_12 = 8'b01111011;
layers_1_spline_weight_13 = 8'b01111011;
layers_1_spline_weight_14 = 8'b01110010;
layers_1_spline_weight_15 = 8'b01111001;
layers_1_spline_weight_16 = 8'b01111000;
layers_1_spline_weight_17 = 8'b01101101;
layers_1_spline_weight_18 = 8'b01000011;
```



```
layers_1_spline_weight_19 = 8'b01010011;
layers_1_spline_weight_20 = 8'b10001101;
layers_1_spline_weight_21 = 8'b01110010;
layers_1_spline_weight_22 = 8'b11111110;
layers_1_spline_weight_23 = 8'b10011111;
layers_1_spline_weight_24 = 8'b01111001;
layers_1_spline_weight_25 = 8'b01110110;
layers_1_spline_weight_26 = 8'b01110011;
layers_1_spline_weight_27 = 8'b10001100;
layers_1_spline_weight_28 = 8'b10011000;
layers_1_spline_weight_29 = 8'b10010100;
layers_1_spline_weight_30 = 8'b10100101;
layers_1_spline_weight_31 = 8'b10000000;
layers_1_spline_weight_32 = 8'b01111001;
layers_1_spline_weight_33 = 8'b01110101;
layers_1_spline_weight_34 = 8'b01111101;
layers_1_spline_weight_35 = 8'b10101110;
layers_1_spline_weight_36 = 8'b10101101;
layers_1_spline_weight_37 = 8'b10111001;
layers_1_spline_weight_38 = 8'b10111101;
layers_1_spline_weight_39 = 8'b01111101;
layers_1_spline_weight_40 = 8'b01111001;
layers_1_spline_weight_41 = 8'b01111001;
layers_1_spline_weight_42 = 8'b01111000;
layers_1_spline_weight_43 = 8'b01111010;
layers_1_spline_weight_44 = 8'b10000000;
layers_1_spline_weight_45 = 8'b01111111;
layers_1_spline_weight_46 = 8'b01111111;
layers_1_spline_weight_47 = 8'b01111010;
layers_1_spline_weight_48 = 8'b01111001;
layers_1_spline_weight_49 = 8'b01110011;
layers_1_spline_weight_50 = 8'b01100111;
layers_1_spline_weight_51 = 8'b10001000;
layers_1_spline_weight_52 = 8'b01110000;
layers_1_spline_weight_53 = 8'b01011001;
layers_1_spline_weight_54 = 8'b10110111;
layers_1_spline_weight_55 = 8'b10000110;
layers_1_spline_weight_56 = 8'b01111001;
layers_1_spline_weight_57 = 8'b01111111;
layers_1_spline_weight_58 = 8'b10000001;
layers_1_spline_weight_59 = 8'b01100000;
layers_1_spline_weight_60 = 8'b10000111;
layers_1_spline_weight_61 = 8'b10000100;
layers_1_spline_weight_62 = 8'b01001100;
layers_1_spline_weight_63 = 8'b01110111;
layers_1_spline_weight_64 = 8'b01111010;
layers_1_spline_weight_65 = 8'b10000100;
layers_1_spline_weight_66 = 8'b10101011;
layers_1_spline_weight_67 = 8'b10011101;
layers_1_spline_weight_68 = 8'b01101000;
layers_1_spline_weight_69 = 8'b10000001;
layers_1_spline_weight_70 = 8'b00000000;
layers_1_spline_weight_71 = 8'b01010110;
layers_2_base_weight_0 = 8'b11111111;
layers_2_base_weight_1 = 8'b00000000;
layers_2_base_weight_2 = 8'b10011100;
layers_2_spline_scaler_0 = 8'b11000111;
layers_2_spline_scaler_1 = 8'b00000000;
layers_2_spline_scaler_2 = 8'b11111111;
layers_2_spline_weight_0 = 8'b10010011;
layers_2_spline_weight_1 = 8'b10010110;
layers_2_spline_weight_2 = 8'b10011001;
layers_2_spline_weight_3 = 8'b10001011;
layers_2_spline_weight_4 = 8'b10011110;
layers_2_spline_weight_5 = 8'b10011010;
layers_2_spline_weight_6 = 8'b01111011;
layers_2_spline_weight_7 = 8'b10001111;
layers_2_spline_weight_8 = 8'b01110110;
layers_2_spline_weight_9 = 8'b00000000;
layers_2_spline_weight_10 = 8'b11111111;
layers_2_spline_weight_11 = 8'b11000101;
```

```

layers_2_spline_weight_12 = 8'b01001101;
layers_2_spline_weight_13 = 8'b10100101;
layers_2_spline_weight_14 = 8'b10100011;
layers_2_spline_weight_15 = 8'b10010100;
layers_2_spline_weight_16 = 8'b10010100;
layers_2_spline_weight_17 = 8'b10011001;
layers_2_spline_weight_18 = 8'b10010000;
layers_2_spline_weight_19 = 8'b10010010;
layers_2_spline_weight_20 = 8'b10010100;
layers_2_spline_weight_21 = 8'b10010010;
layers_2_spline_weight_22 = 8'b10010010;
layers_2_spline_weight_23 = 8'b10010011;
end

// Layer 0: Input to hidden
assign layer0_out_0 = x1 * layers_0_base_weight_0 + x2 * layers_0_base_weight_1;
assign layer0_out_1 = x1 * layers_0_base_weight_2 + x2 * layers_0_base_weight_3;
assign layer0_out_2 = x1 * layers_0_base_weight_4 + x2 * layers_0_base_weight_5;

// Layer 1: Hidden to hidden
assign layer1_out_0 = layer0_out_0 * layers_1_base_weight_0 + layer0_out_1 * layers_1_base_weight_1 +
layer0_out_2 * layers_1_base_weight_2;
assign layer1_out_1 = layer0_out_0 * layers_1_base_weight_3 + layer0_out_1 * layers_1_base_weight_4 +
layer0_out_2 * layers_1_base_weight_5;
assign layer1_out_2 = layer0_out_0 * layers_1_base_weight_6 + layer0_out_1 * layers_1_base_weight_7 +
layer0_out_2 * layers_1_base_weight_8;

// Layer 2: Hidden to output
assign layer2_out = layer1_out_0 * layers_2_base_weight_0 + layer1_out_1 * layers_2_base_weight_1 + layer1_out_2
* layers_2_base_weight_2;

assign y = layer2_out;

endmodule

```

⚠ Caution

「Deprecated Version」 MNIST 版本之 Reference

- 完整 Network 實現 (KAN.v)

```

module KAN (
    input wire clk,
    input wire reset,
    input wire [7:0] in_data [0:783], // 28x28 = 784 pixels, 8-bit each
    output wire [7:0] out_data [0:9] // 10 classes, 8-bit each
);
    // Internal signals for each layer
    wire [7:0] layer1_out [0:63];
    wire [7:0] layer2_out [0:9];

    // Instantiate layers
    KANLayer #(
        .IN_FEATURES(784),
        .OUT_FEATURES(64),
        .BASE_WEIGHT_FILE("C:/intelFPGA_lite/18.1/KAN/base_weight_layer_0.txt"),
        .SPLINE_WEIGHT_FILE("C:/intelFPGA_lite/18.1/KAN/spline_weight_layer_0.txt")
    ) layer1 (
        .clk(clk),
        .reset(reset),
        .in_data(in_data),
        .out_data(layer1_out)
    );

    KANLayer #(
        .IN_FEATURES(64),
        .OUT_FEATURES(10),
        .BASE_WEIGHT_FILE("C:/intelFPGA_lite/18.1/KAN/base_weight_layer_1.txt"),

```

```

        .SPLINE_WEIGHT_FILE("C:/intelFPGA_lite/18.1/KAN/spline_weight_layer_1.txt")
    ) layer2 (
        .clk(clk),
        .reset(reset),
        .in_data(layer1_out),
        .out_data(layer2_out)
    );

    // Connect the final output
    assign out_data = layer2_out;
endmodule

```

FPGA 整合驗證

✔ Success

更換測試資料及 **Network** 設計以求可以將電路設計容納進去 (學習函數擬合簡易乘法 · KAN 的架構為 [2, 3, 3, 1]) 。

💡 Tip

Verilog 僅供模型推論使用。

- Testbench 實現 (tb_KAN.v)

```

`timescale 1ns / 1ps

module tb_KAN;

    // Inputs
    reg clk;
    reg rst;
    reg [31:0] x1;
    reg [31:0] x2;

    // Outputs
    wire [31:0] y;

    // Instantiate the Unit Under Test (UUT)
    KAN uut (
        .clk(clk),
        .rst(rst),
        .x1(x1),
        .x2(x2),
        .y(y)
    );

    initial begin
        // Initialize Inputs
        clk = 0;
        rst = 0;
        x1 = 0;
        x2 = 0;

        // Wait 100 ns for global reset to finish
        #100;

        // Add stimulus here
        rst = 1;
        #10;
        rst = 0;

        // Test case 1
        x1 = 32'd10;
        x2 = 32'd20;
        #20;
    end

```

```

$display("Test case 1: x1 = %d, x2 = %d, y = %d", x1, x2, y);

// Test case 2
x1 = 32'd15;
x2 = 32'd25;
#20;
$display("Test case 2: x1 = %d, x2 = %d, y = %d", x1, x2, y);

// Test case 3
x1 = 32'd100;
x2 = 32'd200;
#20;
$display("Test case 3: x1 = %d, x2 = %d, y = %d", x1, x2, y);

// Finish the simulation
$finish;
end

always #5 clk = ~clk; // Generate clock with 10 ns period (100 MHz)

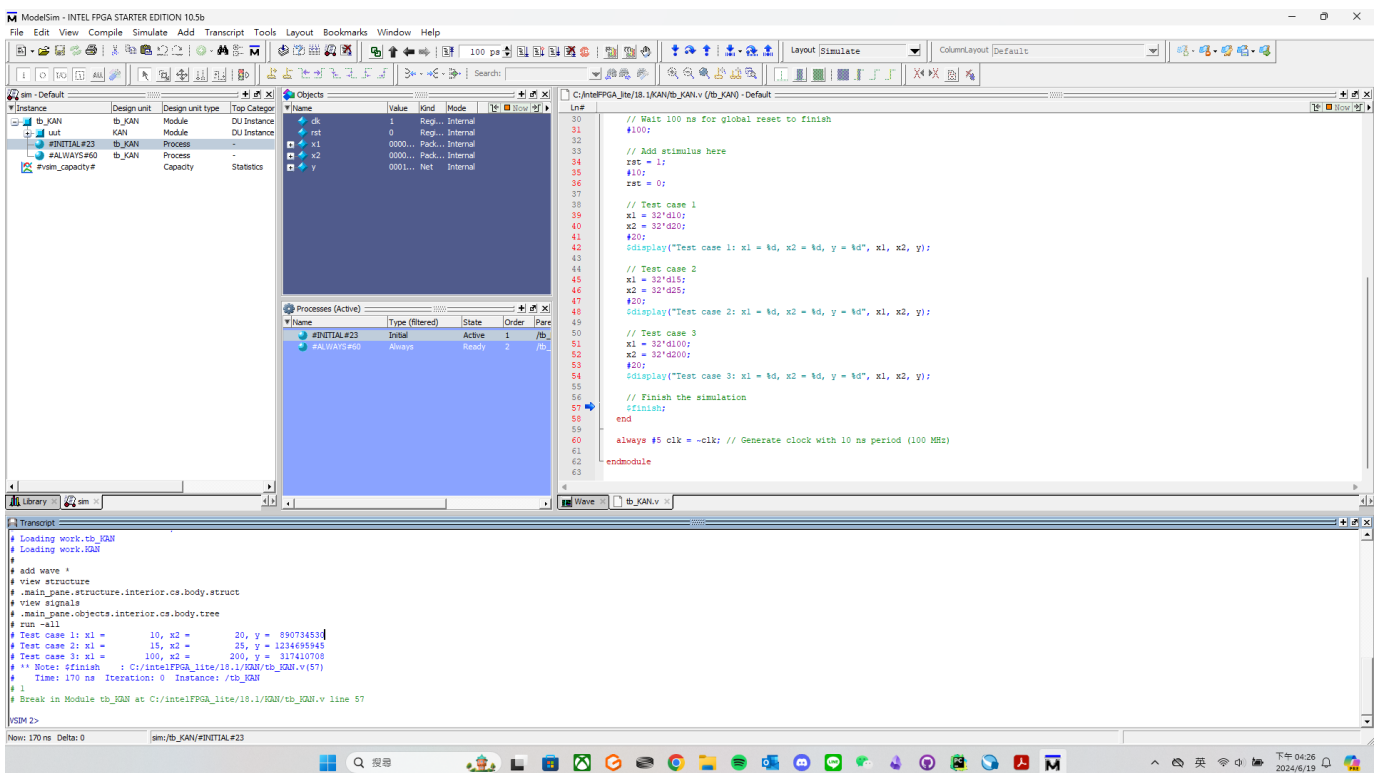
endmodule

```

Warning

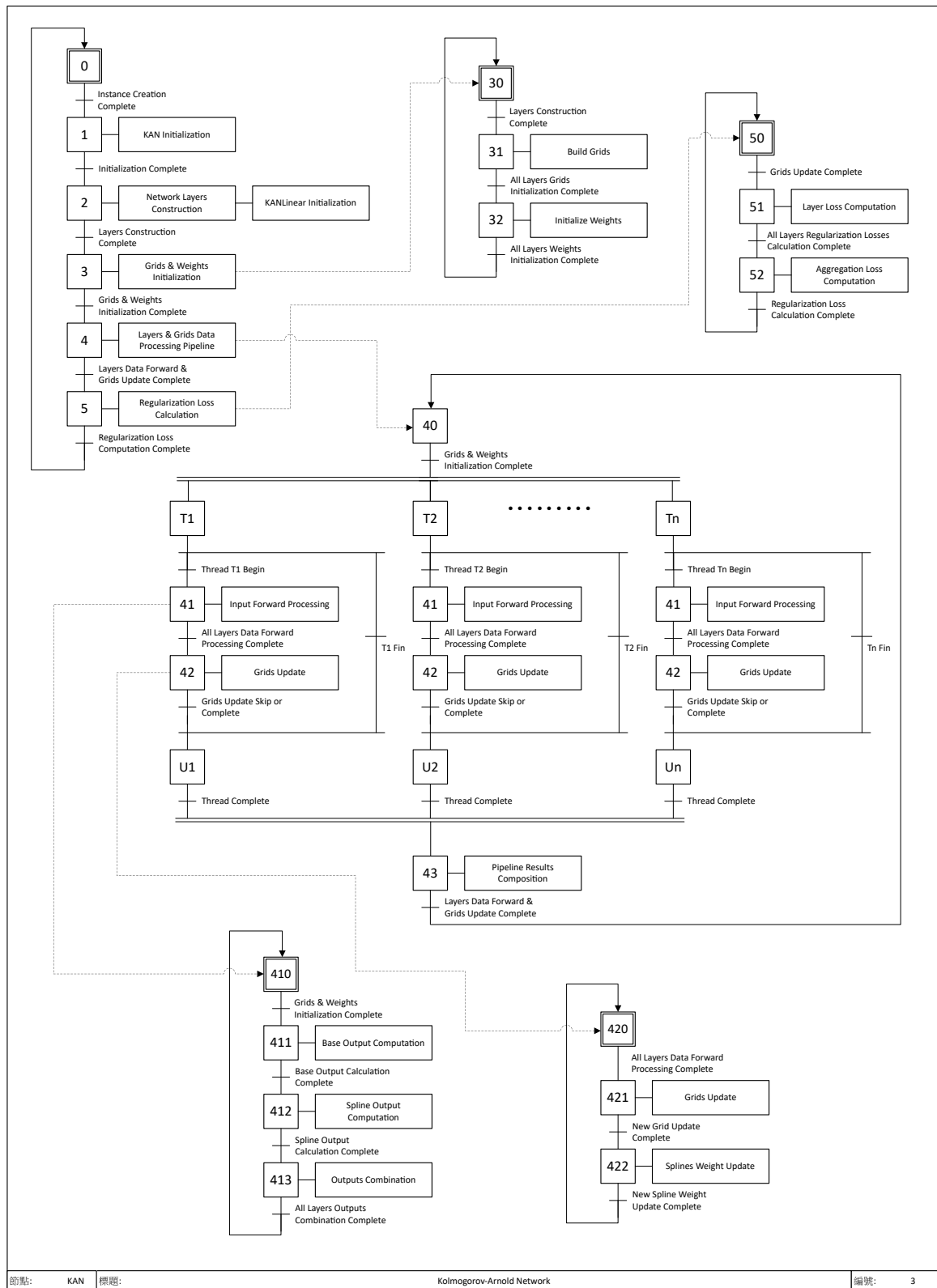
硬體設計完仿真的結果如下，誤差老實說非常大，稍微檢查了一下應該不是 Quantization 後的權重有甚麼問題，而是 Verilog 端在實現 Forward Propagation 的時候有些問題，會需要進一步去排查。

• ModelSim 仿真結果



Pipeline 架構處理

- 功能模組離散事件建模 Grafcet (Pipeline 架構調整)



✓ Success

更換測試資料及 Network 設計以求可以將電路設計容納進去 (學習函數擬合簡易乘法 · KAN 的架構為 [2, 3, 3, 1]) 。

💡 Tip

Verilog 僅供模型推論使用。

- KAN Pipeline 實現

```
module KAN(  
    input wire clk,  
    input wire rst,  
    input wire [31:0] x1,  
    input wire [31:0] x2,  
    output reg [31:0] y  
);  
  
// Intermediate signals  
reg [31:0] layer0_out_0, layer0_out_1, layer0_out_2;  
reg [31:0] layer1_out_0, layer1_out_1, layer1_out_2;  
reg [31:0] layer2_out;  
  
reg [31:0] x1_reg, x2_reg;  
reg [31:0] x1_next, x2_next;  
  
// Declare all weights  
reg [7:0] layers_0_base_weight_0;  
reg [7:0] layers_0_base_weight_1;  
reg [7:0] layers_0_base_weight_2;  
reg [7:0] layers_0_base_weight_3;  
reg [7:0] layers_0_base_weight_4;  
reg [7:0] layers_0_base_weight_5;  
reg [7:0] layers_0_spline_scaler_0;  
reg [7:0] layers_0_spline_scaler_1;  
reg [7:0] layers_0_spline_scaler_2;  
reg [7:0] layers_0_spline_scaler_3;  
reg [7:0] layers_0_spline_scaler_4;  
reg [7:0] layers_0_spline_scaler_5;  
reg [7:0] layers_0_spline_weight_0;  
reg [7:8] layers_0_spline_weight_1;  
reg [7:8] layers_0_spline_weight_2;  
reg [7:8] layers_0_spline_weight_3;  
reg [7:8] layers_0_spline_weight_4;  
reg [7:8] layers_0_spline_weight_5;  
reg [7:8] layers_0_spline_weight_6;  
reg [7:8] layers_0_spline_weight_7;  
reg [7:8] layers_0_spline_weight_8;  
reg [7:8] layers_0_spline_weight_9;  
reg [7:8] layers_0_spline_weight_10;  
reg [7:8] layers_0_spline_weight_11;  
reg [7:8] layers_0_spline_weight_12;  
reg [7:8] layers_0_spline_weight_13;  
reg [7:8] layers_0_spline_weight_14;  
reg [7:8] layers_0_spline_weight_15;  
reg [7:8] layers_0_spline_weight_16;  
reg [7:8] layers_0_spline_weight_17;  
reg [7:8] layers_0_spline_weight_18;  
reg [7:8] layers_0_spline_weight_19;  
reg [7:8] layers_0_spline_weight_20;  
reg [7:8] layers_0_spline_weight_21;  
reg [7:8] layers_0_spline_weight_22;  
reg [7:8] layers_0_spline_weight_23;  
reg [7:8] layers_0_spline_weight_24;  
reg [7:8] layers_0_spline_weight_25;  
reg [7:8] layers_0_spline_weight_26;  
reg [7:8] layers_0_spline_weight_27;  
reg [7:8] layers_0_spline_weight_28;  
reg [7:8] layers_0_spline_weight_29;  
reg [7:8] layers_0_spline_weight_30;  
reg [7:8] layers_0_spline_weight_31;  
reg [7:8] layers_0_spline_weight_32;  
reg [7:8] layers_0_spline_weight_33;  
reg [7:8] layers_0_spline_weight_34;  
reg [7:8] layers_0_spline_weight_35;  
reg [7:8] layers_0_spline_weight_36;  
reg [7:8] layers_0_spline_weight_37;  
reg [7:8] layers_0_spline_weight_38;
```

[illegible]

```

reg [7:8] layers_1_spline_weight_44;
reg [7:8] layers_1_spline_weight_45;
reg [7:8] layers_1_spline_weight_46;
reg [7:8] layers_1_spline_weight_47;
reg [7:8] layers_1_spline_weight_48;
reg [7:8] layers_1_spline_weight_49;
reg [7:8] layers_1_spline_weight_50;
reg [7:8] layers_1_spline_weight_51;
reg [7:8] layers_1_spline_weight_52;
reg [7:8] layers_1_spline_weight_53;
reg [7:8] layers_1_spline_weight_54;
reg [7:8] layers_1_spline_weight_55;
reg [7:8] layers_1_spline_weight_56;
reg [7:8] layers_1_spline_weight_57;
reg [7:8] layers_1_spline_weight_58;
reg [7:8] layers_1_spline_weight_59;
reg [7:8] layers_1_spline_weight_60;
reg [7:8] layers_1_spline_weight_61;
reg [7:8] layers_1_spline_weight_62;
reg [7:8] layers_1_spline_weight_63;
reg [7:8] layers_1_spline_weight_64;
reg [7:8] layers_1_spline_weight_65;
reg [7:8] layers_1_spline_weight_66;
reg [7:8] layers_1_spline_weight_67;
reg [7:8] layers_1_spline_weight_68;
reg [7:8] layers_1_spline_weight_69;
reg [7:8] layers_1_spline_weight_70;
reg [7:8] layers_1_spline_weight_71;
reg [7:8] layers_2_base_weight_0;
reg [7:8] layers_2_base_weight_1;
reg [7:8] layers_2_base_weight_2;
reg [7:8] layers_2_spline_scaler_0;
reg [7:8] layers_2_spline_scaler_1;
reg [7:8] layers_2_spline_scaler_2;
reg [7:8] layers_2_spline_weight_0;
reg [7:8] layers_2_spline_weight_1;
reg [7:8] layers_2_spline_weight_2;
reg [7:8] layers_2_spline_weight_3;
reg [7:8] layers_2_spline_weight_4;
reg [7:8] layers_2_spline_weight_5;
reg [7:8] layers_2_spline_weight_6;
reg [7:8] layers_2_spline_weight_7;
reg [7:8] layers_2_spline_weight_8;
reg [7:8] layers_2_spline_weight_9;
reg [7:8] layers_2_spline_weight_10;
reg [7:8] layers_2_spline_weight_11;
reg [7:8] layers_2_spline_weight_12;
reg [7:8] layers_2_spline_weight_13;
reg [7:8] layers_2_spline_weight_14;
reg [7:8] layers_2_spline_weight_15;
reg [7:8] layers_2_spline_weight_16;
reg [7:8] layers_2_spline_weight_17;
reg [7:8] layers_2_spline_weight_18;
reg [7:8] layers_2_spline_weight_19;
reg [7:8] layers_2_spline_weight_20;
reg [7:8] layers_2_spline_weight_21;
reg [7:8] layers_2_spline_weight_22;
reg [7:8] layers_2_spline_weight_23;

always @(posedge clk or posedge rst) begin
    if (rst) begin
        x1_reg <= 0;
        x2_reg <= 0;
        x1_next <= 0;
        x2_next <= 0;
        layer0_out_0 <= 0;
        layer0_out_1 <= 0;
        layer0_out_2 <= 0;
        layer1_out_0 <= 0;
        layer1_out_1 <= 0;
        layer1_out_2 <= 0;
    end
end

```



```

layer2_out ≤ 0;
y ≤ 0;

// Initialize all weights
layers_0_base_weight_0 ≤ 8'b11111111;
layers_0_base_weight_1 ≤ 8'b01110010;
layers_0_base_weight_2 ≤ 8'b11111001;
layers_0_base_weight_3 ≤ 8'b00000000;
layers_0_base_weight_4 ≤ 8'b11111110;
layers_0_base_weight_5 ≤ 8'b11011100;
layers_0_spline_scaler_0 ≤ 8'b00000000;
layers_0_spline_scaler_1 ≤ 8'b10010000;
layers_0_spline_scaler_2 ≤ 8'b10111000;
layers_0_spline_scaler_3 ≤ 8'b11100101;
layers_0_spline_scaler_4 ≤ 8'b01110111;
layers_0_spline_scaler_5 ≤ 8'b11111111;
layers_0_spline_weight_0 ≤ 8'b10111001;
layers_0_spline_weight_1 ≤ 8'b11000000;
layers_0_spline_weight_2 ≤ 8'b11000100;
layers_0_spline_weight_3 ≤ 8'b10011110;
layers_0_spline_weight_4 ≤ 8'b11101011;
layers_0_spline_weight_5 ≤ 8'b11111110;
layers_0_spline_weight_6 ≤ 8'b01101010;
layers_0_spline_weight_7 ≤ 8'b10101110;
layers_0_spline_weight_8 ≤ 8'b10111000;
layers_0_spline_weight_9 ≤ 8'b10111001;
layers_0_spline_weight_10 ≤ 8'b10111010;
layers_0_spline_weight_11 ≤ 8'b10111010;
layers_0_spline_weight_12 ≤ 8'b10110100;
layers_0_spline_weight_13 ≤ 8'b10111010;
layers_0_spline_weight_14 ≤ 8'b10110111;
layers_0_spline_weight_15 ≤ 8'b10110111;
layers_0_spline_weight_16 ≤ 8'b10111000;
layers_0_spline_weight_17 ≤ 8'b10111010;
layers_0_spline_weight_18 ≤ 8'b10111100;
layers_0_spline_weight_19 ≤ 8'b10110100;
layers_0_spline_weight_20 ≤ 8'b10110010;
layers_0_spline_weight_21 ≤ 8'b10101010;
layers_0_spline_weight_22 ≤ 8'b10100101;
layers_0_spline_weight_23 ≤ 8'b10110110;
layers_0_spline_weight_24 ≤ 8'b10111000;
layers_0_spline_weight_25 ≤ 8'b10111001;
layers_0_spline_weight_26 ≤ 8'b10110101;
layers_0_spline_weight_27 ≤ 8'b10101111;
layers_0_spline_weight_28 ≤ 8'b10010111;
layers_0_spline_weight_29 ≤ 8'b10011001;
layers_0_spline_weight_30 ≤ 8'b10100001;
layers_0_spline_weight_31 ≤ 8'b10110011;
layers_0_spline_weight_32 ≤ 8'b10111000;
layers_0_spline_weight_33 ≤ 8'b10110110;
layers_0_spline_weight_34 ≤ 8'b10111001;
layers_0_spline_weight_35 ≤ 8'b11010101;
layers_0_spline_weight_36 ≤ 8'b11101010;
layers_0_spline_weight_37 ≤ 8'b11111110;
layers_0_spline_weight_38 ≤ 8'b11110000;
layers_0_spline_weight_39 ≤ 8'b10111101;
layers_0_spline_weight_40 ≤ 8'b10111000;
layers_0_spline_weight_41 ≤ 8'b10111011;
layers_0_spline_weight_42 ≤ 8'b10101010;
layers_0_spline_weight_43 ≤ 8'b10000001;
layers_0_spline_weight_44 ≤ 8'b00101110;
layers_0_spline_weight_45 ≤ 8'b00000000;
layers_0_spline_weight_46 ≤ 8'b01000110;
layers_0_spline_weight_47 ≤ 8'b10101010;
layers_1_base_weight_0 ≤ 8'b10101111;
layers_1_base_weight_1 ≤ 8'b11100110;
layers_1_base_weight_2 ≤ 8'b10111110;
layers_1_base_weight_3 ≤ 8'b00101001;
layers_1_base_weight_4 ≤ 8'b00010000;
layers_1_base_weight_5 ≤ 8'b01101101;
layers_1_base_weight_6 ≤ 8'b11111111;

```

```
layers_1_base_weight_7 ≤ 8'b00000010;
layers_1_base_weight_8 ≤ 8'b00000000;
layers_1_spline_scaler_0 ≤ 8'b10011001;
layers_1_spline_scaler_1 ≤ 8'b01111011;
layers_1_spline_scaler_2 ≤ 8'b11101000;
layers_1_spline_scaler_3 ≤ 8'b11000000;
layers_1_spline_scaler_4 ≤ 8'b11111110;
layers_1_spline_scaler_5 ≤ 8'b10001100;
layers_1_spline_scaler_6 ≤ 8'b10110011;
layers_1_spline_scaler_7 ≤ 8'b01000011;
layers_1_spline_scaler_8 ≤ 8'b00000000;
layers_1_spline_weight_0 ≤ 8'b01111001;
layers_1_spline_weight_1 ≤ 8'b01110101;
layers_1_spline_weight_2 ≤ 8'b01101101;
layers_1_spline_weight_3 ≤ 8'b10000011;
layers_1_spline_weight_4 ≤ 8'b01110011;
layers_1_spline_weight_5 ≤ 8'b01100100;
layers_1_spline_weight_6 ≤ 8'b10100010;
layers_1_spline_weight_7 ≤ 8'b10000010;
layers_1_spline_weight_8 ≤ 8'b01111001;
layers_1_spline_weight_9 ≤ 8'b01111010;
layers_1_spline_weight_10 ≤ 8'b01111010;
layers_1_spline_weight_11 ≤ 8'b01110101;
layers_1_spline_weight_12 ≤ 8'b01111011;
layers_1_spline_weight_13 ≤ 8'b01111011;
layers_1_spline_weight_14 ≤ 8'b01110010;
layers_1_spline_weight_15 ≤ 8'b01111001;
layers_1_spline_weight_16 ≤ 8'b01111000;
layers_1_spline_weight_17 ≤ 8'b01101101;
layers_1_spline_weight_18 ≤ 8'b01000011;
layers_1_spline_weight_19 ≤ 8'b01010011;
layers_1_spline_weight_20 ≤ 8'b10001101;
layers_1_spline_weight_21 ≤ 8'b01110010;
layers_1_spline_weight_22 ≤ 8'b11111110;
layers_1_spline_weight_23 ≤ 8'b10011111;
layers_1_spline_weight_24 ≤ 8'b01111001;
layers_1_spline_weight_25 ≤ 8'b01110110;
layers_1_spline_weight_26 ≤ 8'b01110011;
layers_1_spline_weight_27 ≤ 8'b10001100;
layers_1_spline_weight_28 ≤ 8'b10011000;
layers_1_spline_weight_29 ≤ 8'b10010100;
layers_1_spline_weight_30 ≤ 8'b10100101;
layers_1_spline_weight_31 ≤ 8'b10000000;
layers_1_spline_weight_32 ≤ 8'b01111001;
layers_1_spline_weight_33 ≤ 8'b01110101;
layers_1_spline_weight_34 ≤ 8'b01111101;
layers_1_spline_weight_35 ≤ 8'b10101110;
layers_1_spline_weight_36 ≤ 8'b10101101;
layers_1_spline_weight_37 ≤ 8'b10111001;
layers_1_spline_weight_38 ≤ 8'b10111101;
layers_1_spline_weight_39 ≤ 8'b01111101;
layers_1_spline_weight_40 ≤ 8'b01111001;
layers_1_spline_weight_41 ≤ 8'b01111001;
layers_1_spline_weight_42 ≤ 8'b01111000;
layers_1_spline_weight_43 ≤ 8'b01111010;
layers_1_spline_weight_44 ≤ 8'b10000000;
layers_1_spline_weight_45 ≤ 8'b01111111;
layers_1_spline_weight_46 ≤ 8'b01111111;
layers_1_spline_weight_47 ≤ 8'b01111010;
layers_1_spline_weight_48 ≤ 8'b01111001;
layers_1_spline_weight_49 ≤ 8'b01110011;
layers_1_spline_weight_50 ≤ 8'b01100111;
layers_1_spline_weight_51 ≤ 8'b10001000;
layers_1_spline_weight_52 ≤ 8'b01110000;
layers_1_spline_weight_53 ≤ 8'b01011001;
layers_1_spline_weight_54 ≤ 8'b10110111;
layers_1_spline_weight_55 ≤ 8'b10000110;
layers_1_spline_weight_56 ≤ 8'b01111001;
layers_1_spline_weight_57 ≤ 8'b01111111;
layers_1_spline_weight_58 ≤ 8'b10000001;
layers_1_spline_weight_59 ≤ 8'b01100000;
```

```

layers_1_spline_weight_60 ≤ 8'b10000111;
layers_1_spline_weight_61 ≤ 8'b10000100;
layers_1_spline_weight_62 ≤ 8'b01001100;
layers_1_spline_weight_63 ≤ 8'b01110111;
layers_1_spline_weight_64 ≤ 8'b01111010;
layers_1_spline_weight_65 ≤ 8'b10000100;
layers_1_spline_weight_66 ≤ 8'b10101011;
layers_1_spline_weight_67 ≤ 8'b10011101;
layers_1_spline_weight_68 ≤ 8'b01101000;
layers_1_spline_weight_69 ≤ 8'b10000001;
layers_1_spline_weight_70 ≤ 8'b00000000;
layers_1_spline_weight_71 ≤ 8'b01010110;
layers_2_base_weight_0 ≤ 8'b11111111;
layers_2_base_weight_1 ≤ 8'b00000000;
layers_2_base_weight_2 ≤ 8'b10011100;
layers_2_spline_scaler_0 ≤ 8'b11000111;
layers_2_spline_scaler_1 ≤ 8'b00000000;
layers_2_spline_scaler_2 ≤ 8'b11111111;
layers_2_spline_weight_0 ≤ 8'b10010011;
layers_2_spline_weight_1 ≤ 8'b10010110;
layers_2_spline_weight_2 ≤ 8'b10011001;
layers_2_spline_weight_3 ≤ 8'b10001011;
layers_2_spline_weight_4 ≤ 8'b10011110;
layers_2_spline_weight_5 ≤ 8'b10011010;
layers_2_spline_weight_6 ≤ 8'b01111011;
layers_2_spline_weight_7 ≤ 8'b10001111;
layers_2_spline_weight_8 ≤ 8'b01110110;
layers_2_spline_weight_9 ≤ 8'b00000000;
layers_2_spline_weight_10 ≤ 8'b11111111;
layers_2_spline_weight_11 ≤ 8'b11000101;
layers_2_spline_weight_12 ≤ 8'b01001101;
layers_2_spline_weight_13 ≤ 8'b10100101;
layers_2_spline_weight_14 ≤ 8'b10100011;
layers_2_spline_weight_15 ≤ 8'b10010100;
layers_2_spline_weight_16 ≤ 8'b10010100;
layers_2_spline_weight_17 ≤ 8'b10011001;
layers_2_spline_weight_18 ≤ 8'b10010000;
layers_2_spline_weight_19 ≤ 8'b10010010;
layers_2_spline_weight_20 ≤ 8'b10010100;
layers_2_spline_weight_21 ≤ 8'b10010010;
layers_2_spline_weight_22 ≤ 8'b10010010;
layers_2_spline_weight_23 ≤ 8'b10010011;
end else begin
    // Pipeline stage 1: Input to hidden
    x1_reg ≤ x1;
    x2_reg ≤ x2;
    layer0_out_0 ≤ x1 * layers_0_base_weight_0 + x2 * layers_0_base_weight_1;
    layer0_out_1 ≤ x1 * layers_0_base_weight_2 + x2 * layers_0_base_weight_3;
    layer0_out_2 ≤ x1 * layers_0_base_weight_4 + x2 * layers_0_base_weight_5;

    // Pipeline stage 2: Hidden to hidden
    x1_next ≤ x1_reg;
    x2_next ≤ x2_reg;
    layer1_out_0 ≤ layer0_out_0 * layers_1_base_weight_0 + layer0_out_1 * layers_1_base_weight_1 +
    layer0_out_2 * layers_1_base_weight_2;
    layer1_out_1 ≤ layer0_out_0 * layers_1_base_weight_3 + layer0_out_1 * layers_1_base_weight_4 +
    layer0_out_2 * layers_1_base_weight_5;
    layer1_out_2 ≤ layer0_out_0 * layers_1_base_weight_6 + layer0_out_1 * layers_1_base_weight_7 +
    layer0_out_2 * layers_1_base_weight_8;

    // Pipeline stage 3: Hidden to output
    layer2_out ≤ layer1_out_0 * layers_2_base_weight_0 + layer1_out_1 * layers_2_base_weight_1 +
    layer1_out_2 * layers_2_base_weight_2;

    // Output assignment
    y ≤ layer2_out;
end
end

endmodule

```

- Testbench 實現 (tb_KAN.v)

```
`timescale 1ns / 1ps

module tb_KAN;

    // Inputs
    reg clk;
    reg rst;
    reg [31:0] x1;
    reg [31:0] x2;

    // Outputs
    wire [31:0] y;

    // Instantiate the Unit Under Test (UUT)
    KAN uut (
        .clk(clk),
        .rst(rst),
        .x1(x1),
        .x2(x2),
        .y(y)
    );

    initial begin
        // Initialize Inputs
        clk = 0;
        rst = 0;
        x1 = 0;
        x2 = 0;

        // Wait 100 ns for global reset to finish
        #100;

        // Add stimulus here
        rst = 1;
        #10;
        rst = 0;

        // Test case 1
        x1 = 32'd10;
        x2 = 32'd20;
        #10; // Wait for one clock cycle

        // Test case 2
        x1 = 32'd15;
        x2 = 32'd25;
        #10; // Wait for one clock cycle

        // Test case 3
        x1 = 32'd100;
        x2 = 32'd200;
        #10; // Wait for one clock cycle

        // Continue providing new inputs if needed
        // ...

        // Wait for enough time to allow pipeline to process all inputs
        #50;

        // Check results
        // Due to pipeline, the results will be delayed
        // Check results after appropriate delay
        $display("Test case 1 result: y = %d (expected value)", y); // Replace with expected value
        #10;
        $display("Test case 2 result: y = %d (expected value)", y); // Replace with expected value
        #10;
        $display("Test case 3 result: y = %d (expected value)", y); // Replace with expected value

        // Finish the simulation
    end
endmodule
```

```

$finish;
end

always #5 clk = ~clk; // Generate clock with 10 ns period (100 MHz)

endmodule

```

• ModelSim 仿真結果

The screenshot displays the ModelSim - Intel FPGA Starter Edition 10.5b interface. The main editor shows the Verilog code for a module named `tb_KAN`. The code includes a clock generation block, input and output registers, and a testbench structure. The simulation is running, and the transcript shows the following results:

```

# Loading work.tb_KAN
# Loading work.KAN
# add wave *
# view structure
# .main_pane.structure.interior.cs.body.struct
# view signals
# .main_pane.objects.interior.cs.body.tree
# run -all
# Test case 1 result: y = 1000500 (expected value)
# Test case 2 result: y = 1000500 (expected value)
# Test case 3 result: y = 1000500 (expected value)
# ** Note: $finish : C:/intelFPGA_lite/10.1/KAN/tb_KAN.v(69)
# Time: 210 ns Iteration: 0 Instance: /tb_KAN
# i
# Break in Module tb_KAN at C:/intelFPGA_lite/10.1/KAN/tb_KAN.v line 69
V$IM 2>
Now: 210 ns Delta: 0
sm:/tb_KAN/#INITIAL#23
Ln: 69 Col: 0 READ

```