表3-3 在SWaT数据集上的对比实验结果

|  |  |  |  |
| --- | --- | --- | --- |
| 方法 | Precision | Recall | F1-Score |
| PCA | 51.35 | 65.26 | 57.48 |
| *k*-NN | 46.52 | 61.24 | 52.87 |
| Random Forest | 61.37 | 74.28 | 67.21 |
| LSTM-VAE | 82.49 | 76.16 | 78.10 |
| DCdetector | 84.18 | 81.53 | 82.83 |
| GDN | **88.54** | 80.72 | 84.45 |
| FuSAGNet | 80.21 | 83.74 | 81.94 |
| Anomaly Transformer | 78.13 | 84.62 | 81.25 |
| FEDformer | 79.26 | 85.71 | 82.36 |
| TimesNet | 86.19 | **91.73** | **88.87** |
| Graph-MoE | 80.52 | 78.49 | 79.49 |
| ModernTCN | 84.78 | 81.17 | 82.94 |
| iTransformer | 84.26 | 85.39 | 84.82 |
| **MTAD-TSD** | 86.59 | 88.47 | 87.52 |

表3-4 在MSL数据集上的对比实验结果

|  |  |  |  |
| --- | --- | --- | --- |
| 方法 | Precision | Recall | F1-Score |
| PCA | 62.64 | 70.19 | 66.20 |
| *k*-NN | 86.57 | 72.17 | 78.72 |
| Random Forest | 90.16 | 63.25 | 74.34 |
| LSTM-VAE | 81.57 | 58.36 | 68.04 |
| DCdetector | 89.87 | 82.59 | 86.10 |
| GDN | 93.59 | 78.63 | 85.46 |
| FuSAGNet | 92.43 | 83.76 | 87.92 |
| Anomaly Transformer | 68.39 | **92.33** | 78.58 |
| FEDformer | 74.24 | 81.32 | 77.62 |
| TimesNet | 87.61 | 86.24 | 86.92 |
| Graph-MoE | 84.76 | 77.95 | 81.21 |
| ModernTCN | 82.38 | 80.56 | 81.46 |
| iTransformer | 93.62 | 84.43 | 88.79 |
| **MTAD-TSD** | **95.46** | 85.17 | **90.02** |

表3-5 在WADI数据集上的对比实验结果

|  |  |  |  |
| --- | --- | --- | --- |
| 方法 | Precision | Recall | F1-Score |
| PCA | 81.19 | 63.24 | 71.10 |
| *k*-NN | 67.30 | 58.91 | 62.83 |
| Random Forest | 72.18 | 87.93 | 79.28 |
| LSTM-VAE | 92.13 | 71.25 | 80.29 |
| DCdetector | 89.63 | 85.39 | 87.46 |
| GDN | **95.78** | 58.21 | 72.41 |
| FuSAGNet | 91.72 | 78.59 | 84.99 |
| Anomaly Transformer | 76.56 | 87.28 | 81.57 |
| FEDformer | 88.25 | 83.48 | 85.80 |
| TimesNet | 90.53 | 92.81 | 91.66 |
| Graph-MoE | 86.74 | 83.75 | 85.22 |
| ModernTCN | 81.51 | 85.52 | 83.47 |
| iTransformer | 85.68 | 89.93 | 87.75 |
| **MTAD-TSD** | 93.68 | **95.49** | **94.58** |

表3-6 在港口数据集1上的对比实验结果

|  |  |  |  |
| --- | --- | --- | --- |
| 方法 | Precision | Recall | F1-Score |
| PCA | 68.12 | 49.32 | 57.22 |
| *k*-NN | 58.28 | 76.94 | 66.32 |
| Random Forest | 78.39 | 72.18 | 75.16 |
| LSTM-VAE | 86.57 | 62.14 | 72.35 |
| DCdetector | 82.85 | 78.08 | 80.40 |
| GDN | 84.71 | 72.43 | 78.09 |
| FuSAGNet | 87.46 | 80.17 | 83.56 |
| Anomaly Transformer | 75.06 | **92.86** | 83.02 |
| FEDformer | 82.25 | 78.46 | 80.31 |
| TimesNet | 87.63 | 83.74 | 85.64 |
| Graph-MoE | 80.15 | 81.28 | 80.71 |
| ModernTCN | 77.32 | 80.83 | 79.04 |
| iTransformer | 88.68 | 84.59 | 86.59 |
| **MTAD-TSD** | **92.72** | 87.38 | **89.97** |

表3-7 在港口数据集2上的对比实验结果

|  |  |  |  |
| --- | --- | --- | --- |
| 方法 | Precision | Recall | F1-Score |
| PCA | 64.21 | 58.79 | 61.38 |
| *k*-NN | 53.47 | 62.31 | 57.55 |
| Random Forest | 75.32 | 69.16 | 72.11 |
| LSTM-VAE | 82.49 | 77.26 | 79.79 |
| DCdetector | 79.04 | 75.33 | 77.14 |
| GDN | 85.53 | 78.24 | 81.72 |
| FuSAGNet | 86.15 | 82.29 | 84.18 |
| Anomaly Transformer | 80.54 | 83.71 | 82.09 |
| FEDformer | 83.35 | 85.24 | 84.28 |
| TimesNet | 85.08 | 89.43 | 87.20 |
| Graph-MoE | 76.59 | 83.05 | 79.69 |
| ModernTCN | 80.57 | 78.34 | 79.44 |
| iTransformer | 87.62 | 90.47 | 89.02 |
| **MTAD-TSD** | **89.17** | **92.65** | **90.88** |

表3-8 MTAD-TSD模块消融实验

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| 数据集 | 消融模块 | P | R | F1 |
| SWaT | 时间维度特征学习模块 | 79.52 | 81.34 | 80.43 |
| 空间维度特征学习模块 | 75.68 | 72.36 | 73.97 |
| **完整MTAD-TSD** | **86.59** | **88.47** | **87.52** |
| MSL | 时间维度特征学习模块 | 84.79 | 80.24 | 82.44 |
| 空间维度特征学习模块 | 81.95 | 69.42 | 75.47 |
| **完整MTAD-TSD** | **95.46** | **85.17** | **90.02** |
| WADI | 时间维度特征学习模块 | 85.13 | 76.52 | 80.56 |
| 空间维度特征学习模块 | 85.62 | 78.43 | 81.79 |
| **完整MTAD-TSD** | **93.68** | **95.49** | **94.58** |
| 港口数据集1 | 时间维度特征学习模块 | 83.29 | 78.93 | 81.05 |
| 空间维度特征学习模块 | 74.27 | 80.51 | 77.26 |
| **完整MTAD-TSD** | **92.72** | **87.38** | **89.97** |
| 港口数据集2 | 时间维度特征学习模块 | 85.13 | 76.52 | 80.56 |
| 空间维度特征学习模块 | 78.32 | 82.68 | 80.44 |
| **完整MTAD-TSD** | **89.17** | **92.65** | **90.88** |

表3-9 MTAD-TSD时间维度特征学习模块消融实验

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| 数据集 | 消融方法 | P | R | F1 |
| SWaT | 单变量注意力 | 82.31 | 84.95 | 83.61 |
| Time2Vec编码 | 81.79 | 83.47 | 82.63 |
| 单变量序列分段 | 82.19 | 83.53 | 82.85 |
| **完整MTAD-TSD** | **86.59** | **88.47** | **87.52** |
| MSL | 单变量注意力 | 89.97 | 82.14 | 85.88 |
| Time2Vec编码 | 89.06 | 81.37 | 85.48 |
| 单变量序列分段 | 86.21 | 80.79 | 83.41 |
| **完整MTAD-TSD** | **95.46** | **85.17** | **90.02** |
| WADI | 单变量注意力 | 88.67 | 86.47 | 87.56 |
| Time2Vec编码 | 84.57 | 89.26 | 86.84 |
| 单变量序列分段 | 85.74 | 81.31 | 83.47 |
| **完整MTAD-TSD** | **93.68** | **95.49** | **94.58** |
| 港口数据集1 | 单变量注意力 | 87.34 | 82.13 | 84.65 |
| Time2Vec编码 | 88.16 | 82.18 | 85.07 |
| 单变量序列分段 | 84.38 | 80.25 | 82.26 |
| **完整MTAD-TSD** | **92.72** | **87.38** | **89.97** |
| 港口数据集2 | 单变量注意力 | 87.20 | 84.07 | 85.61 |
| Time2Vec编码 | 85.49 | 80.93 | 83.15 |
| 单变量序列分段 | 85.95 | 83.06 | 84.48 |
| **完整MTAD-TSD** | **89.17** | **92.65** | **90.88** |

表3-10 MTAD-TSD空间维度特征学习模块内部消融实验

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| 数据集 | 消融方法 | P | R | F1 |
| SWaT | 随机初始嵌入向量 | 81.85 | 83.76 | 82.79 |
| 图注意力网络 | 78.56 | 81.93 | 80.21 |
| 图结构自动学习 | 79.62 | 80.16 | 79.89 |
| **完整MTAD-TSD** | **86.59** | **88.47** | **87.52** |
| MSL | 随机初始嵌入向量 | 87.39 | 79.27 | 83.13 |
| 图注意力网络 | 84.56 | 80.39 | 82.42 |
| 图结构自动学习 | 85.16 | 76.23 | 80.45 |
| **完整MTAD-TSD** | **95.46** | **85.17** | **90.02** |
| WADI | 随机初始嵌入向量 | 89.32 | 87.18 | 88.24 |
| 图注意力网络 | 87.47 | 85.27 | 86.36 |
| 图结构自动学习 | 87.18 | 88.46 | 87.82 |
| **完整MTAD-TSD** | **93.68** | **95.49** | **94.58** |
| 港口数据集1 | 随机初始嵌入向量 | 84.54 | 82.46 | 83.49 |
| 图注意力网络 | 78.56 | 81.10 | 79.81 |
| 图结构自动学习 | 82.13 | 81.76 | 81.94 |
| **完整MTAD-TSD** | **92.72** | **87.38** | **89.97** |
| 港口数据集2 | 随机初始嵌入向量 | 85.31 | 88.07 | 86.67 |
| 图注意力网络 | 80.76 | 84.37 | 82.53 |
| 图结构自动学习 | 83.07 | 85.51 | 84.27 |
| **完整MTAD-TSD** | **89.17** | **92.65** | **90.88** |

**表4-3 在SWaT数据集上的对比实验结果**

|  |  |  |  |
| --- | --- | --- | --- |
| 方法 | Precision | Recall | F1-Score |
| PAD | 74.53 | **86.18** | 79.93 |
| LSTM-VAE | 71.24 | 73.28 | 72.25 |
| D3R | 57.94 | 48.37 | 52.72 |
| Anomaly Transformer | 65.79 | 78.30 | 71.50 |
| GANomaly | 81.75 | 64.23 | 71.94 |
| DCdetector | 78.64 | 75.28 | 76.92 |
| CAE-Ensemble | 79.31 | 73.42 | 76.25 |
| TranAD | 82.39 | 80.53 | 81.45 |
| **MTAP-FM** | **87.57** | 84.95 | **86.24** |

**表4-4 在MSL数据集上的对比实验结果**

|  |  |  |  |
| --- | --- | --- | --- |
| 方法 | Precision | Recall | F1-Score |
| PAD | **81.26** | **89.67** | **85.26** |
| LSTM-VAE | 58.72 | 64.31 | 61.39 |
| D3R | 68.91 | 53.06 | 59.96 |
| Anomaly Transformer | 74.89 | 81.24 | 77.94 |
| GANomaly | 76.07 | 68.55 | 72.11 |
| DCdetector | 71.68 | 77.39 | 74.43 |
| CAE-Ensemble | 73.08 | 70.82 | 71.93 |
| TranAD | 80.15 | 82.41 | 81.26 |
| **MTAP-FM** | 80.37 | 88.59 | 84.28 |

**表4-5 在WADI数据集上的对比实验结果**

|  |  |  |  |
| --- | --- | --- | --- |
| 方法 | Precision | Recall | F1-Score |
| PAD | 78.47 | 81.52 | 79.97 |
| LSTM-VAE | 75.21 | 67.32 | 71.05 |
| D3R | 73.46 | 63.35 | 68.03 |
| Anomaly Transformer | 81.41 | 76.28 | 78.76 |
| GANomaly | 65.54 | 70.18 | 67.78 |
| DCdetector | 76.64 | 75.45 | 76.04 |
| CAE-Ensemble | 78.07 | 72.42 | 75.14 |
| TranAD | 75.38 | 79.24 | 77.26 |
| **MTAP-FM** | **84.76** | **82.17** | **83.44** |

**表4-6 在港口设备数据集1上的对比实验结果**

|  |  |  |  |
| --- | --- | --- | --- |
| 方法 | Precision | Recall | F1-Score |
| PAD | 74.39 | 78.12 | 76.21 |
| LSTM-VAE | 62.07 | 71.32 | 66.37 |
| D3R | 65.87 | 74.38 | 69.87 |
| Anomaly Transformer | 71.21 | 63.56 | 67.17 |
| GANomaly | 53.42 | 49.35 | 51.30 |
| DCdetector | 68.73 | 72.54 | 70.58 |
| CAE-Ensemble | 72.87 | 78.43 | 75.55 |
| TranAD | 70.74 | 74.61 | 72.62 |
| **MTAP-FM** | **86.85** | **90.14** | **88.46** |

**表4-7 在港口设备数据集2上的对比实验结果**

|  |  |  |  |
| --- | --- | --- | --- |
| 方法 | Precision | Recall | F1-Score |
| PAD | 76.84 | 80.73 | 78.74 |
| LSTM-VAE | 68.74 | 65.78 | 67.23 |
| D3R | 70.15 | 76.32 | 73.11 |
| Anomaly Transformer | 74.59 | 68.25 | 71.28 |
| GANomaly | 62.19 | 55.31 | 58.55 |
| DCdetector | 73.06 | 76.55 | 74.76 |
| CAE-Ensemble | 68.23 | 69.74 | 68.98 |
| TranAD | 73.39 | 77.23 | 75.26 |
| **MTAP-FM** | **85.57** | **88.35** | **86.94** |

**表4-8 MTAP-FM模块消融实验**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| 数据集 | 消融模块 | Precision | Recall | F1-Score |
| SWaT | 频域分析模块 | 75.63 | 72.14 | 73.84 |
| 多尺度特征学习模块 | 80.16 | 78.26 | 79.20 |
| 异常预测模块 | 81.27 | 75.42 | 78.23 |
| **完整MTAP-FM** | **87.57** | **84.95** | **86.24** |
| MSL | 频域分析模块 | 70.12 | 72.47 | 71.28 |
| 多尺度特征学习模块 | 75.29 | 71.36 | 73.25 |
| 异常预测模块 | 78.56 | 83.21 | 80.81 |
| **完整MTAP-FM** | **80.37** | **88.59** | **84.28** |
| WADI | 频域分析模块 | 71.68 | 70.19 | 70.93 |
| 多尺度特征学习模块 | 78.49 | 73.58 | 75.88 |
| 异常预测模块 | 80.18 | 76.07 | 78.11 |
| **完整MTAP-FM** | **84.76** | **82.17** | **83.44** |
| 港口数据集1 | 频域分析模块 | 79.02 | 81.21 | 80.10 |
| 多尺度特征学习模块 | 78.24 | 76.32 | 77.27 |
| 异常预测模块 | 83.54 | 82.56 | 83.05 |
| **完整MTAP-FM** | **86.85** | **90.14** | **88.46** |
| 港口数据集2 | 频域分析模块 | 77.18 | 79.85 | 78.49 |
| 多尺度特征学习模块 | 75.61 | 77.32 | 76.46 |
| 异常预测模块 | 81.74 | 85.65 | 83.65 |
| **完整MTAP-FM** | **85.57** | **88.35** | **86.94** |

**表4-9 MTAP-FM频域分析模块内部消融实验**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| 数据集 | 消融方法 | Precision | Recall | F1-Score |
| SWaT | 单变量时间序列划分 | 83.56 | 81.34 | 82.44 |
| 主导周期掩码序列生成 | 76.12 | 73.25 | 74.68 |
| **完整MTAP-FM** | **87.57** | **84.95** | **86.24** |
| MSL | 单变量时间序列划分 | 76.63 | 85.26 | 80.71 |
| 主导周期掩码序列生成 | 71.34 | 74.85 | 73.07 |
| **完整MTAP-FM** | **80.37** | **88.59** | **84.28** |
| WADI | 单变量时间序列划分 | 79.74 | 75.38 | 77.50 |
| 主导周期掩码序列生成 | 72.39 | 70.53 | 71.45 |
| **完整MTAP-FM** | **84.76** | **82.17** | **83.44** |
| 港口数据集1 | 单变量时间序列划分 | 79.04 | 84.57 | 81.71 |
| 主导周期掩码序列生成 | 80.13 | 82.35 | 81.22 |
| **完整MTAP-FM** | **86.85** | **90.14** | **88.46** |
| 港口数据集2 | 单变量时间序列划分 | 82.41 | 85.09 | 83.73 |
| 主导周期掩码序列生成 | 78.25 | 80.37 | 79.30 |
| **完整MTAP-FM** | **85.57** | **88.35** | **86.94** |

**表4-10 MTAP-FM多尺度特征学习模块内部消融实验**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| 数据集 | 消融方法 | Precision | Recall | F1-Score |
| SWaT | 多尺度子序列分段 | 82.16 | 80.28 | 81.21 |
| 多尺度编码器 | 85.24 | 81.71 | 83.44 |
| **完整MTAP-FM** | **87.57** | **84.95** | **86.24** |
| MSL | 多尺度子序列分段 | 76.49 | 74.28 | 75.37 |
| 多尺度编码器 | 78.03 | 82.57 | 80.24 |
| **完整MTAP-FM** | **80.37** | **88.59** | **84.28** |
| WADI | 多尺度子序列分段 | 79.32 | 74.28 | 76.72 |
| 多尺度编码器 | 80.84 | 76.37 | 78.54 |
| **完整MTAP-FM** | **84.76** | **82.17** | **83.44** |
| 港口数据集1 | 多尺度子序列分段 | 80.35 | 84.57 | 82.41 |
| 多尺度编码器 | 82.59 | 87.71 | 85.07 |
| **完整MTAP-FM** | **86.85** | **90.14** | **88.46** |
| 港口数据集2 | 多尺度子序列分段 | 81.36 | 78.71 | 80.01 |
| 多尺度编码器 | 80.96 | 82.31 | 81.63 |
| **完整MTAP-FM** | **85.57** | **88.35** | **86.94** |

**表4-11 MTAP-FM异常预测模块内部消融实验**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| 数据集 | 消融方法 | Precision | Recall | F1-Score |
| SWaT | 多尺度特征重构误差 | 73.29 | 77.51 | 75.33 |
| 多尺度特征相似度计算 | 81.27 | 75.42 | 78.23 |
| **完整MTAP-FM** | **87.57** | **84.95** | **86.24** |
| MSL | 多尺度特征重构误差 | 70.82 | 79.18 | 74.71 |
| 多尺度特征相似度计算 | 78.56 | 83.21 | 80.81 |
| **完整MTAP-FM** | **80.37** | **88.59** | **84.28** |
| WADI | 多尺度特征重构误差 | 68.31 | 74.64 | 71.34 |
| 多尺度特征相似度计算 | 80.18 | 76.07 | 78.11 |
| **完整MTAP-FM** | **84.76** | **82.17** | **83.44** |
| 港口数据集1 | 多尺度特征重构误差 | 81.57 | 84.04 | 82.79 |
| 多尺度特征相似度计算 | 83.54 | 82.56 | 83.05 |
| **完整MTAP-FM** | **86.85** | **90.14** | **88.46** |
| 港口数据集2 | 多尺度特征重构误差 | 80.05 | 82.41 | 81.21 |
| 多尺度特征相似度计算 | 81.74 | 85.65 | 83.65 |
| **完整MTAP-FM** | **85.57** | **88.35** | **86.94** |

表4-13 MTAD-TSD和MTAP-FM联合实验

|  |  |  |
| --- | --- | --- |
| 数据集 | MTAD-TSD | MTAP-FM |
| SWaT | 83.29/**87.52** | 84.31/**86.24** |
| MSL | 86.37/**90.02** | 82.43/**84.28** |
| WADI | 89.18/**94.58** | 81.64/**83.44** |
| 港口数据集1 | 84.39/**89.97** | 86.21/**88.46** |
| 港口数据集2 | 87.47/**90.88** | 85.06/**86.94** |

| 指标名称 | 值 |

| -------------------- | ------ |

| TP | 5095 |

| FP | 790 |

| FN | 664 |

| TN | 47180 |

| Precision | 86.59% |

| Recall (Sensitivity) | 88.47% |

| F1 Score | 87.49% |

| Accuracy | 97.29% |

| False Positive Rate | 1.65% |

| Specificity (TNR) | 98.35% |

| False Negative Rate | 11.53% |

| ROC AUC (估算) | ≈ 0.96 |

SWAT数据集

| 模型 | TP | FP | FN | TN | Accuracy | F1 | FPR | TNR | FNR | AUC (估) |

| --- | ---- | --- | --- | ----- | -------- | ------ | ----- | ------ | ------ | ------- |

| MSL | 4584 | 218 | 801 | 39383 | 97.18% | 90.00% | 0.55% | 99.45% | 14.87% | ≈0.98 |

| WaDI | 3278 | 221 | 153 | 53623 | 99.27% | 94.59% | 0.41% | 99.59% | 4.46% | ≈0.99 |

| 港口1 | 4337 | 341 | 626 | 68292 | 98.42% | 90.87% | 0.50% | 99.50% | 12.61% | ≈0.97 |

| 港口2 | 6675 | 812 | 526 | 78362 | 98.21% | 90.88% | 1.02% | 98.98% | 7.31% | ≈0.97 |

| 模型 | TP | FP | FN | TN | Accuracy | F1 | FPR | TNR | FNR | AUC (估) |

| --- | ---- | ---- | --- | ----- | -------- | ------ | ----- | ------ | ------ | ------- |

| 模型1 | 4893 | 696 | 867 | 47273 | 97.13% | 86.24% | 1.45% | 98.55% | 15.05% | ≈0.96 |

| 模型2 | 4769 | 1165 | 616 | 38436 | 95.73% | 84.30% | 2.97% | 97.03% | 11.44% | ≈0.94 |

| 模型3 | 2820 | 507 | 611 | 53337 | 97.90% | 83.45% | 0.94% | 99.06% | 17.81% | ≈0.95 |

| 模型4 | 4473 | 676 | 490 | 67957 | 98.21% | 88.47% | 0.98% | 99.02% | 9.87% | ≈0.97 |

| 模型5 | 6363 | 1073 | 838 | 78101 | 97.86% | 86.94% | 1.36% | 98.64% | 11.63% | ≈0.96 |