**3A-TTA Framework**

- **Activation-Based Pseudo-Labeling**
  - Pseudo label
  - Similarity between liveness feature and class activation map
  \[
  y = \begin{cases} 
  1, & \text{if } \text{sim}(\mathbf{f}_1, \mathbf{A}_l) \geq \text{sim}(\mathbf{f}_1, \mathbf{A}_s) \\
  0, & \text{if } \text{sim}(\mathbf{f}_1, \mathbf{A}_l) < \text{sim}(\mathbf{f}_1, \mathbf{A}_s) 
  \end{cases}
  \]
  - Liveness loss
  \[
  L_l = - \sum \log \text{CF}(\mathbf{f}) + (1 - \bar{y}) \log(1 - \text{CF}(\mathbf{f}))
  \]

- **Anti-Forgetting Feature Learning**
  - Reliable feature selection
  - Anti-forgetting liveness loss
  \[
  L_{aff} = - \sum \log \text{CF}(\mathbf{f}) + (1 - \bar{y}) \log(1 - \text{CF}(\mathbf{f}))
  \]

- **Asymmetric Prototype Contrastive Learning**
  - Asymmetric prototype contrastive loss
  \[
  L_{apc} = - \log \frac{\exp \left( \text{sim}(\mathbf{f}_s, \mathbf{f}_p) \right)}{\sum_j \frac{\exp \left( \text{sim}(\mathbf{f}_s, \mathbf{f}_j) \right)}{N_{s}}} - \log \frac{\exp \left( \text{sim}(\mathbf{f}_l, \mathbf{f}_p) \right)}{\sum_j \frac{\exp \left( \text{sim}(\mathbf{f}_l, \mathbf{f}_j) \right)}{N_{l}}}
  \]

**Experiments**

- **Datasets**
  - OULU-NPU (O), MSU-MFSD (M), CASIA-MFSD (C), Replay-Attack (I), 3DMAD (D), and HKBU-MARs (H)

- **Evaluation Metrics**
  - Half Total Error Rate (HTER) ↓
  - Area Under Curve (AUC) ↑

---

**Ablation Study**

| Method | Total Loss $L_T$ | pseudo-labeling Mechanisms | Feature Selection | OCMl → D | OCMl → C | OCMl → I | Experiment | Augmentation
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>M0</td>
<td>28.26</td>
<td>84.97</td>
<td>Omni + Clue + CPM</td>
<td>28.85</td>
<td>29.78</td>
<td>28.26</td>
<td>84.97</td>
<td>28.85</td>
</tr>
<tr>
<td>M1</td>
<td>✓</td>
<td>84.97</td>
<td>Omni + Clue + CPM</td>
<td>28.85</td>
<td>29.78</td>
<td>28.26</td>
<td>84.97</td>
<td>28.85</td>
</tr>
<tr>
<td>M2</td>
<td>✓</td>
<td>88.41</td>
<td>Omni + Clue + CPM</td>
<td>29.04</td>
<td>28.94</td>
<td>29.04</td>
<td>88.41</td>
<td>29.04</td>
</tr>
<tr>
<td>M3</td>
<td>✓</td>
<td>88.41</td>
<td>Omni + Clue + CPM</td>
<td>29.04</td>
<td>28.94</td>
<td>29.04</td>
<td>88.41</td>
<td>29.04</td>
</tr>
<tr>
<td>M4</td>
<td>✓</td>
<td>88.41</td>
<td>Omni + Clue + CPM</td>
<td>29.04</td>
<td>28.94</td>
<td>29.04</td>
<td>88.41</td>
<td>29.04</td>
</tr>
<tr>
<td>M5</td>
<td>✓</td>
<td>88.41</td>
<td>Omni + Clue + CPM</td>
<td>29.04</td>
<td>28.94</td>
<td>29.04</td>
<td>88.41</td>
<td>29.04</td>
</tr>
<tr>
<td>M6</td>
<td>✓</td>
<td>88.41</td>
<td>Omni + Clue + CPM</td>
<td>29.04</td>
<td>28.94</td>
<td>29.04</td>
<td>88.41</td>
<td>29.04</td>
</tr>
<tr>
<td>M7</td>
<td>✓</td>
<td>88.41</td>
<td>Omni + Clue + CPM</td>
<td>29.04</td>
<td>28.94</td>
<td>29.04</td>
<td>88.41</td>
<td>29.04</td>
</tr>
</tbody>
</table>

**Proposed TTA-FAS Benchmark**

- **Dataset**
  - OULU-NPU (O), MSU-MFSD (M), CASIA-MFSD (C), Replay-Attack (I), 3DMAD (D), and HKBU-MARs (H)

- **Evaluation Metrics**
  - Half Total Error Rate (HTER) ↓
  - Area Under Curve (AUC) ↑

**Experimental Comparisons**

- **Method**
  - OCMl → M: OCMl → D → D (O), OCMl → C → C (C), OCMl → I → I (I)
  - Experiment: Omni + Clue + CPM
  - Augmentation: Omni + Clue + CPM

| Method | Total Loss $L_T$ | pseudo-labeling Mechanisms | Feature Selection | OCMl → D | OCMl → C | OCMl → I | Experiment | Augmentation
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>M0</td>
<td>28.26</td>
<td>84.97</td>
<td>Omni + Clue + CPM</td>
<td>28.85</td>
<td>29.78</td>
<td>28.26</td>
<td>84.97</td>
<td>28.85</td>
</tr>
<tr>
<td>M1</td>
<td>✓</td>
<td>84.97</td>
<td>Omni + Clue + CPM</td>
<td>28.85</td>
<td>29.78</td>
<td>28.26</td>
<td>84.97</td>
<td>28.85</td>
</tr>
<tr>
<td>M2</td>
<td>✓</td>
<td>88.41</td>
<td>Omni + Clue + CPM</td>
<td>29.04</td>
<td>28.94</td>
<td>29.04</td>
<td>88.41</td>
<td>29.04</td>
</tr>
<tr>
<td>M3</td>
<td>✓</td>
<td>88.41</td>
<td>Omni + Clue + CPM</td>
<td>29.04</td>
<td>28.94</td>
<td>29.04</td>
<td>88.41</td>
<td>29.04</td>
</tr>
<tr>
<td>M4</td>
<td>✓</td>
<td>88.41</td>
<td>Omni + Clue + CPM</td>
<td>29.04</td>
<td>28.94</td>
<td>29.04</td>
<td>88.41</td>
<td>29.04</td>
</tr>
<tr>
<td>M5</td>
<td>✓</td>
<td>88.41</td>
<td>Omni + Clue + CPM</td>
<td>29.04</td>
<td>28.94</td>
<td>29.04</td>
<td>88.41</td>
<td>29.04</td>
</tr>
<tr>
<td>M6</td>
<td>✓</td>
<td>88.41</td>
<td>Omni + Clue + CPM</td>
<td>29.04</td>
<td>28.94</td>
<td>29.04</td>
<td>88.41</td>
<td>29.04</td>
</tr>
<tr>
<td>M7</td>
<td>✓</td>
<td>88.41</td>
<td>Omni + Clue + CPM</td>
<td>29.04</td>
<td>28.94</td>
<td>29.04</td>
<td>88.41</td>
<td>29.04</td>
</tr>
</tbody>
</table>

---

**Test-Time Adaptation for Robust Face Anti-Spoofing**

Pei-Kai Huang, Chen-Yu Lu, Shu-Jung Chang, Jun-Xiong Chong, and Chiou-Ting Hsu

National Tsing Hua University, Taiwan