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PL-HLANet: a semi-supervised approach for tunnel boring machine disc cutter wear prediction

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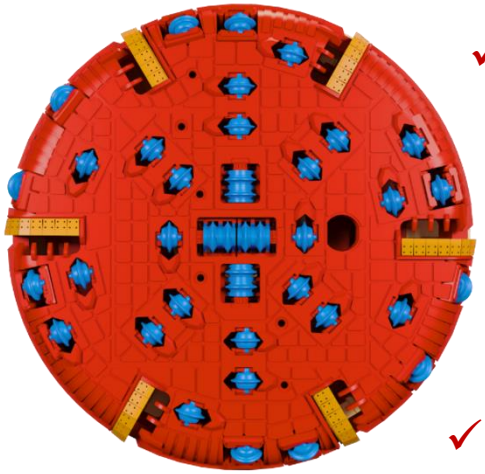
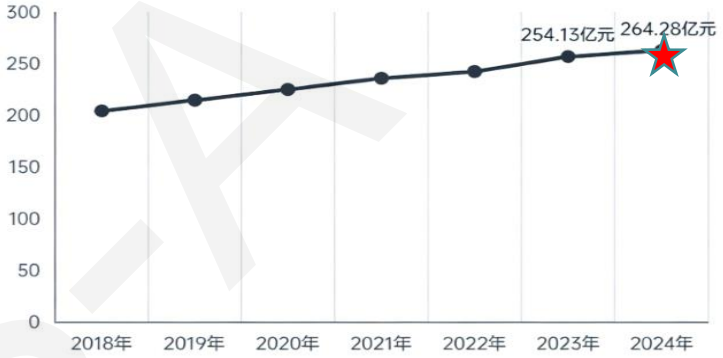
Backgrounds

Tunneling Boring Machine



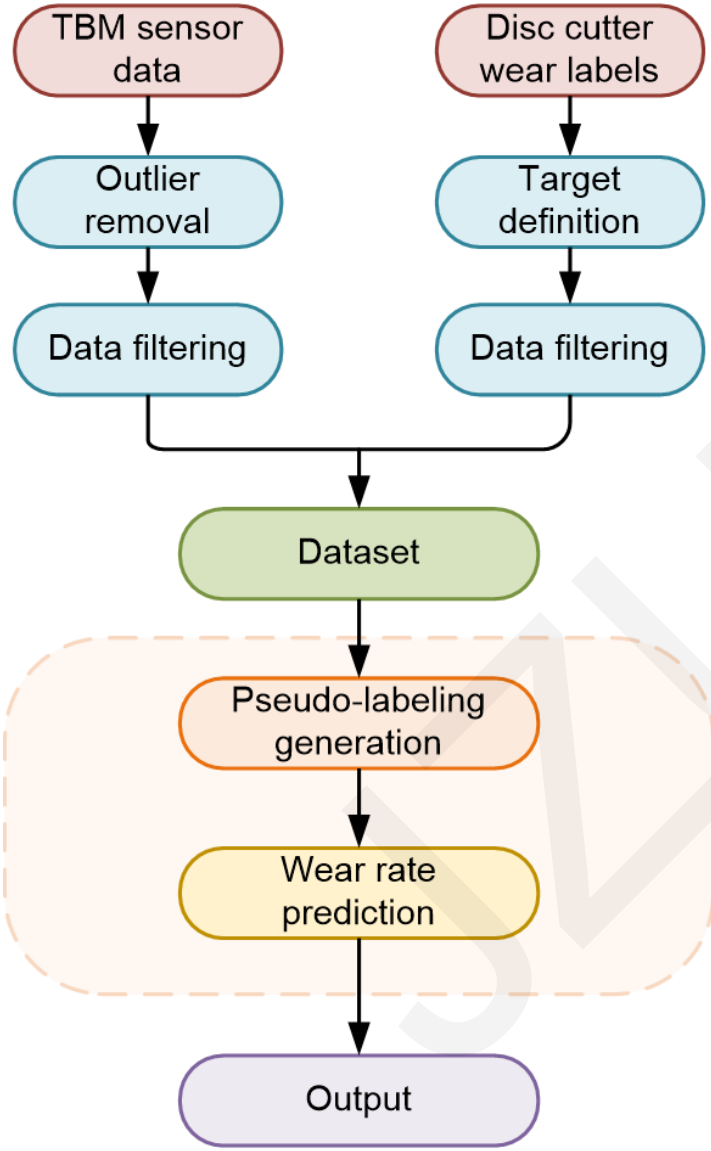
- ✓ **High efficiency**
- ✓ **Eco-friendly**
- ✓ **Stable quality**
- ✓ **Highly automated**
- ✓ **Safe**



TBMs have become the **core equipment** for tunnel excavation.

Various types of unexpected disc cutter wear can lead to **high economic costs** and **project delays**, and may even trigger **major safety accidents** such as machine jamming or cave-ins.

Proposed method



Data Preparation

- Outlier removal & noise filtering
- Dynamic target definition
- Structured dataset construction

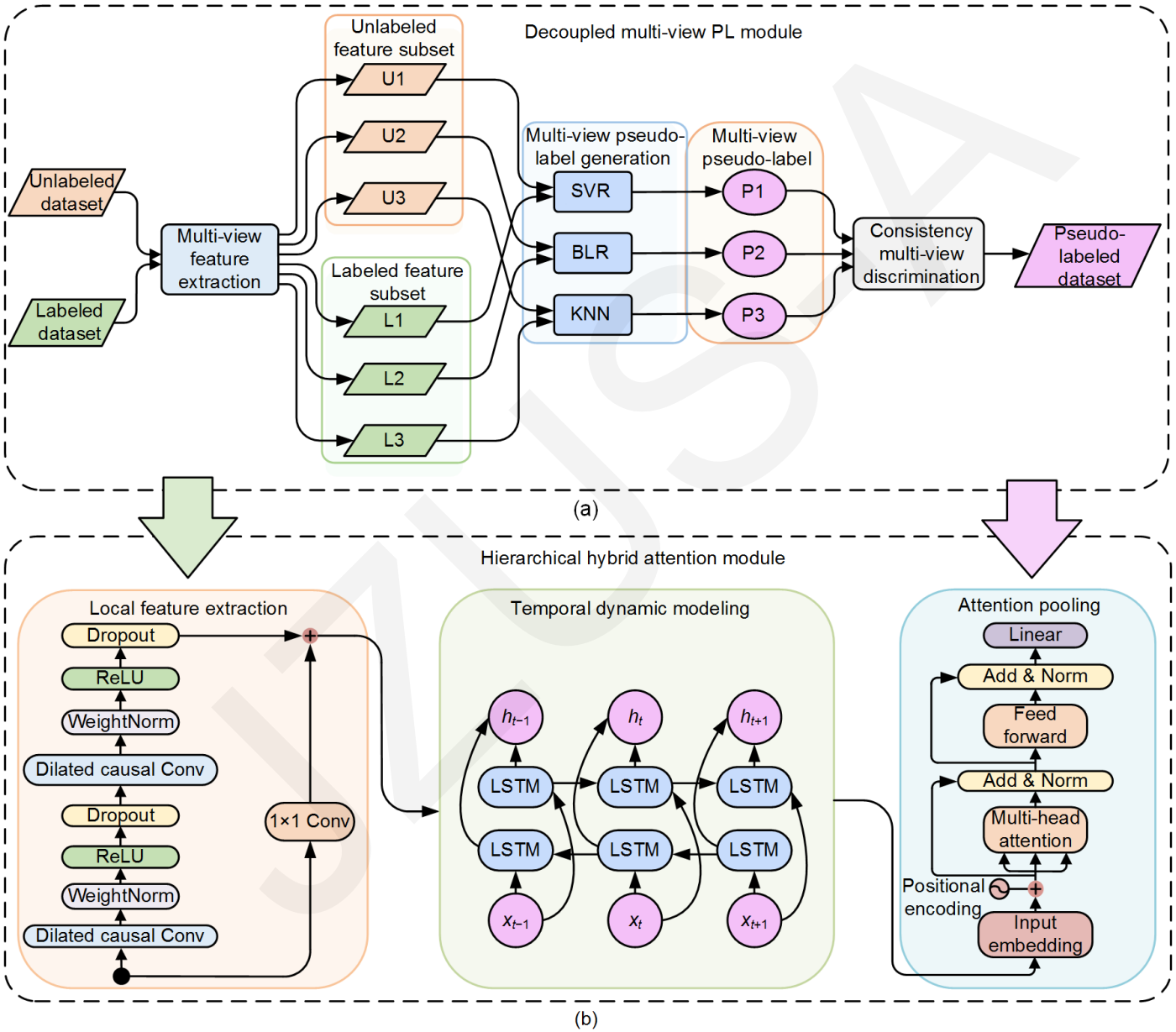
Proposed Framework

- Pseudo-labeling generation
- Wear rate prediction

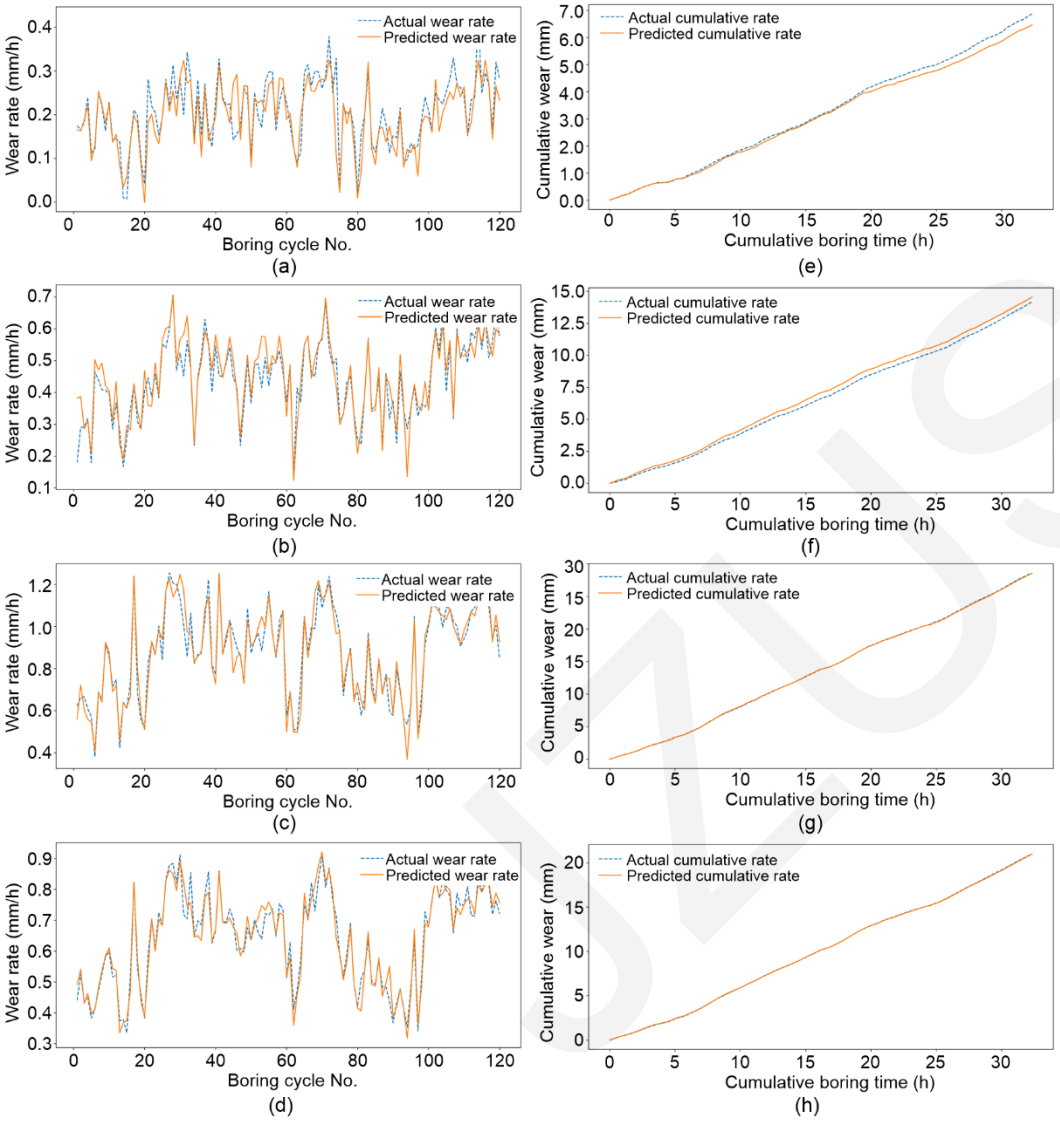
Final Output

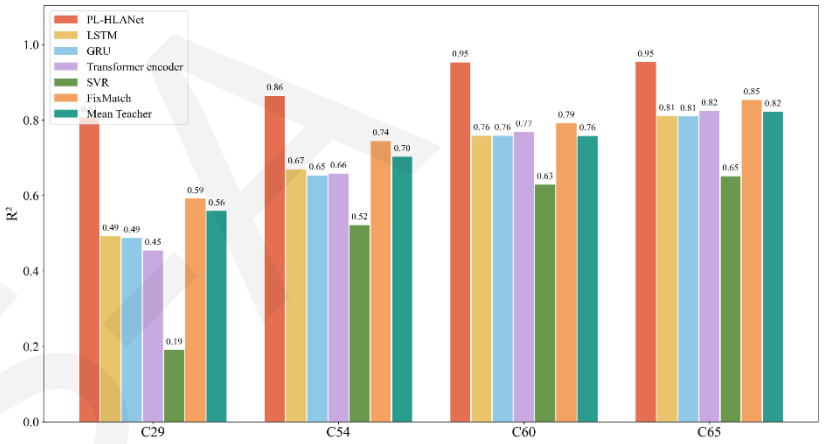
- Real-time wear rate estimation

Proposed PL-HLANet



Prediction Performance





- **High Accuracy**: $R^2 > 0.80$, 7.37ms latency.
- **Superiority**: Outperforms all baseline models.
- **Robustness**: Exceptional prediction on noisy, low-SNR cutters (C29).

Conclusions

- **Innovative Framework:** We proposed PL-HLANet, a decoupled semi-supervised predictive framework, to successfully address the dual challenge of labeled data scarcity and complex operating conditions in TBM disc cutter wear prediction.
- **Superior Performance & Practicality:** The framework consistently outperforms both classic supervised models (SVR, LSTM) and advanced semi-supervised baselines (Mean Teacher, FixMatch). Furthermore, it demonstrates high computational efficiency with a single-sample latency of only 7.37 ms, making it highly practical for real-world industrial scenarios.
- **Robust Architectural Design:** The hierarchical TCN-BiLSTM-Attention architecture ensures powerful feature learning capabilities and excellent robustness, particularly for making accurate predictions on challenging, low-SNR samples like the C29 cutter. Additionally, the decoupled pseudo-labeling (PL) module is crucial for correcting sampling bias and regularizing the model.
- **Future Directions:** Subsequent research will extend the model to provide early warnings for abnormal failure modes (e.g., chipping and fracturing). We will also explore advanced self-supervised learning to further minimize reliance on labeled data , and focus on practical engineering deployment with online learning for continuous optimization