From Vibration to Motor Current: A Cross-Modal Meta-Learning-Driven Fault Diagnosis Framework for Harmonic Drive of Industrial Robots

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Abstract: Harmonic drives are critical components in industrial robots, yet their fault diagnosis remains challenging due to sensor limitations. Vibration signals, although informative, are often impractical in industrial settings, whereas motor current signals are more accessible but contain weaker fault signatures for the mechanical components driven by the motor due to their indirect nature. To bridge this gap, this study proposes a cross-modal meta-learning network (CROMET-Net), which transfers diagnostic knowledge from vibration signals (strong modality) to motor current signals (weak modality) through a meta-learning-based alignment strategy. The core design involves a dual-level cross-modal alignment mechanism embedded into the inner loop of meta-training, which enforces both class-level consistency and modality-invariant feature learning. A three-stage training strategy is adopted, including vibration-based pretraining, meta-alignment across modalities, and fine-tuning using only motor current data. Experimental results on a harmonic drive testbed demonstrate that CROMET-Net significantly outperforms conventional current-based methods and existing cross-modal baselines, highlighting the effectiveness of the proposed method in transferring diagnostic knowledge across modalities.