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CdualTAL: multi-domain tool wear prediction using a dual-channel Transformer and cross-attention network

Key words: Multi-domain features; Dual-channel; Feature fusion; Tool wear; Attention mechanism; Feature enhancement

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Motivation

1. Current intelligent manufacturing relies heavily on multi-domain sensor features to monitor tool wear. However, these features inevitably introduce numerous irrelevant or noisy components that dilute the model's focus on the most predictive attributes.

2. Existing methods often struggle to balance feature usage. Models relying on single-domain features overlook cross-domain interactions, while hybrid models tend to discard "weak" features that may contain critical complementary information essential for a holistic understanding.

3. Tool wear is a continuous degradation process characterized by complex evolutionary patterns. Effectively capturing long-range temporal dependencies within these sequences remains a significant challenge for many deep learning architectures.

Main idea

1. We propose CdualTAL algorithm using a correlation-adaptive feature selection module to identify strong features dynamically. A dual-channel Transformer encoder then processes these strong features and global multi-domain features in parallel to prevent noise interference.

2. To address the fusion challenge, a custom cross-attention mechanism with feature-type gating is designed. This component adaptively balances the feature streams by sharpening focus on strong features while judiciously integrating valuable information from weak ones.

3. For temporal modeling, a hierarchical long short-term memory (LSTM) decoder with residual connections is employed. This deep structure mines the fused sequences to capture long-term dependencies and ensure stable prediction across all wear stages.

Method

1. CdualTAL architecture integrates four primary components to achieve high-accuracy predictions. The process begins by transforming multi-sensor signals into multi-domain interpretable features.

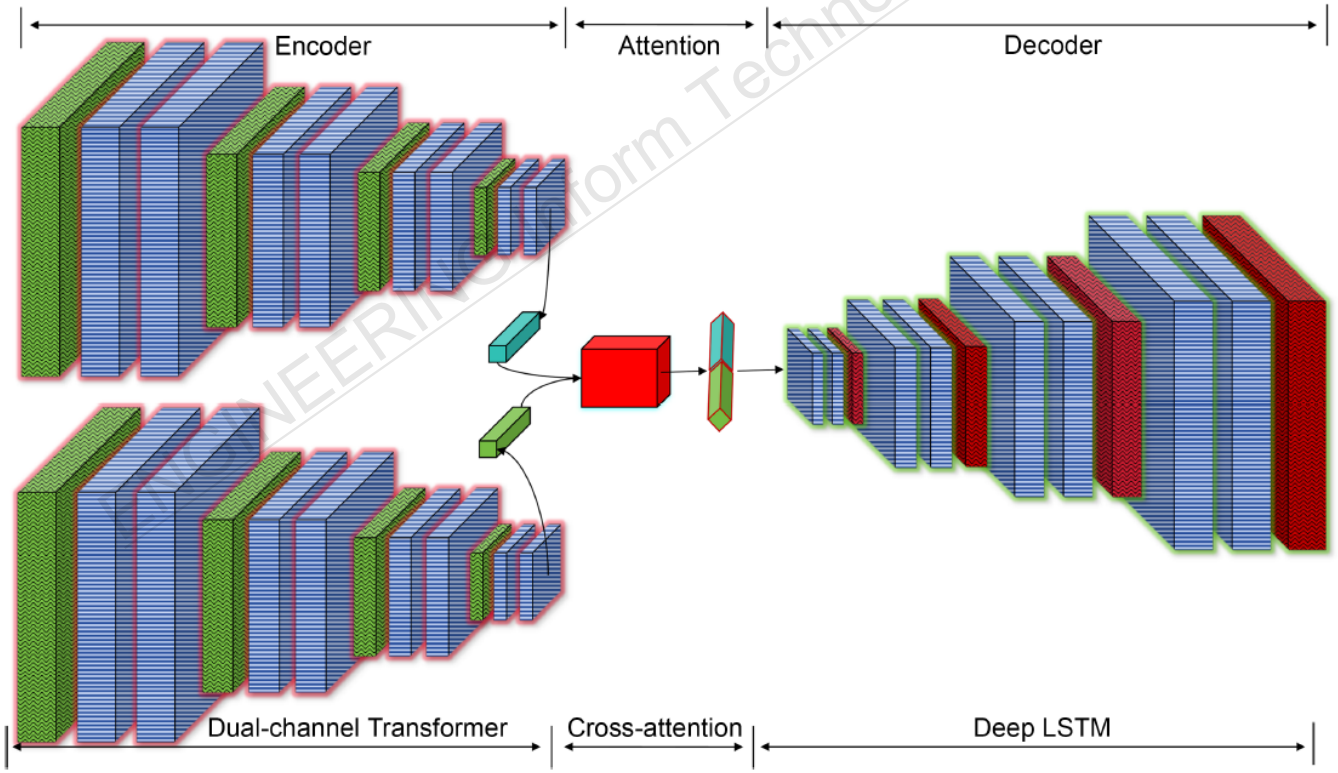

Fig. 1 Main structure of CdualTAL

Method (Cont'd)

2. We employ a dual-channel Transformer encoder to isolate features. One channel processes the full multi-domain feature set, while the other independently handles the selected strong features. This parallel structure effectively prevents irrelevant features from contaminating key signals.

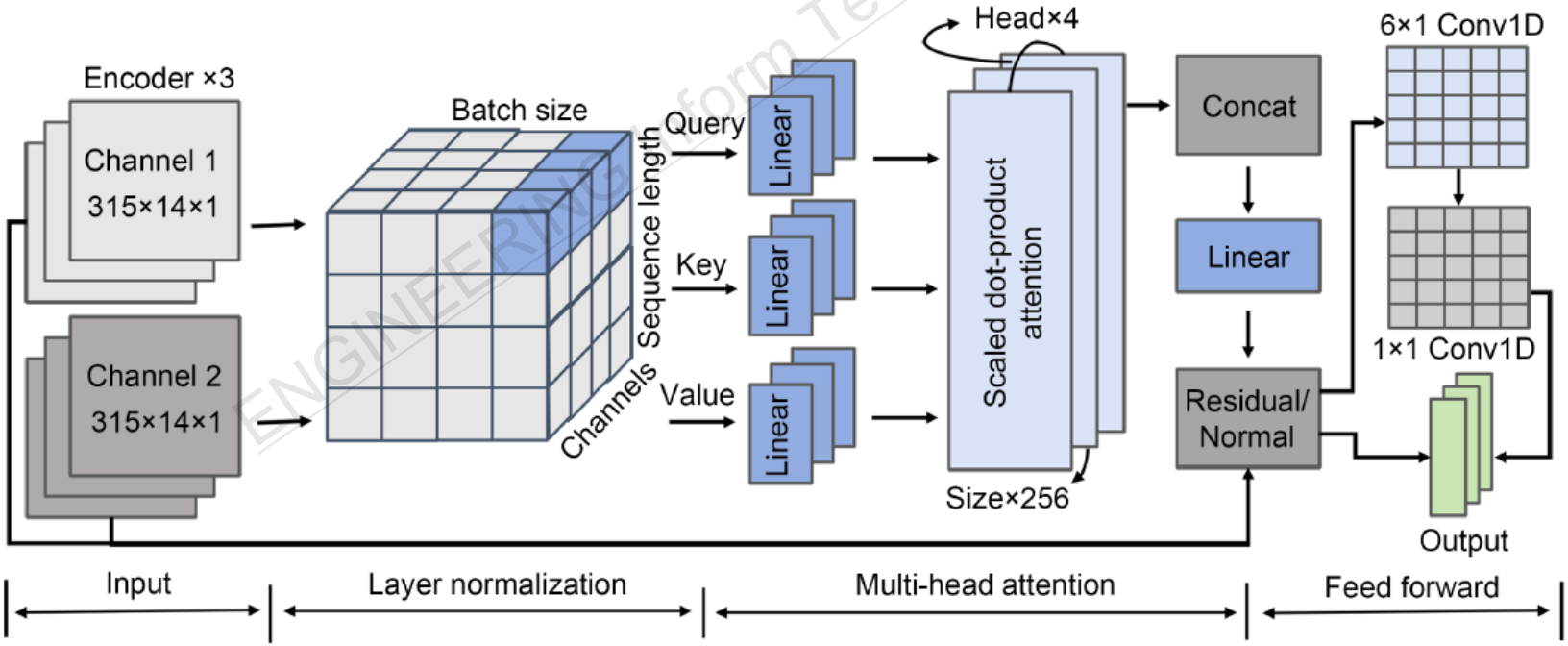

Fig. 2 Structure of the dual-channel encoder

Method (Cont'd)

3. The outputs from the two encoders are fused via a custom cross-attention module. Unlike traditional concatenation, this mechanism uses scaled dot-product weighting to emphasize the most relevant features while preserving potential key information from weaker features.

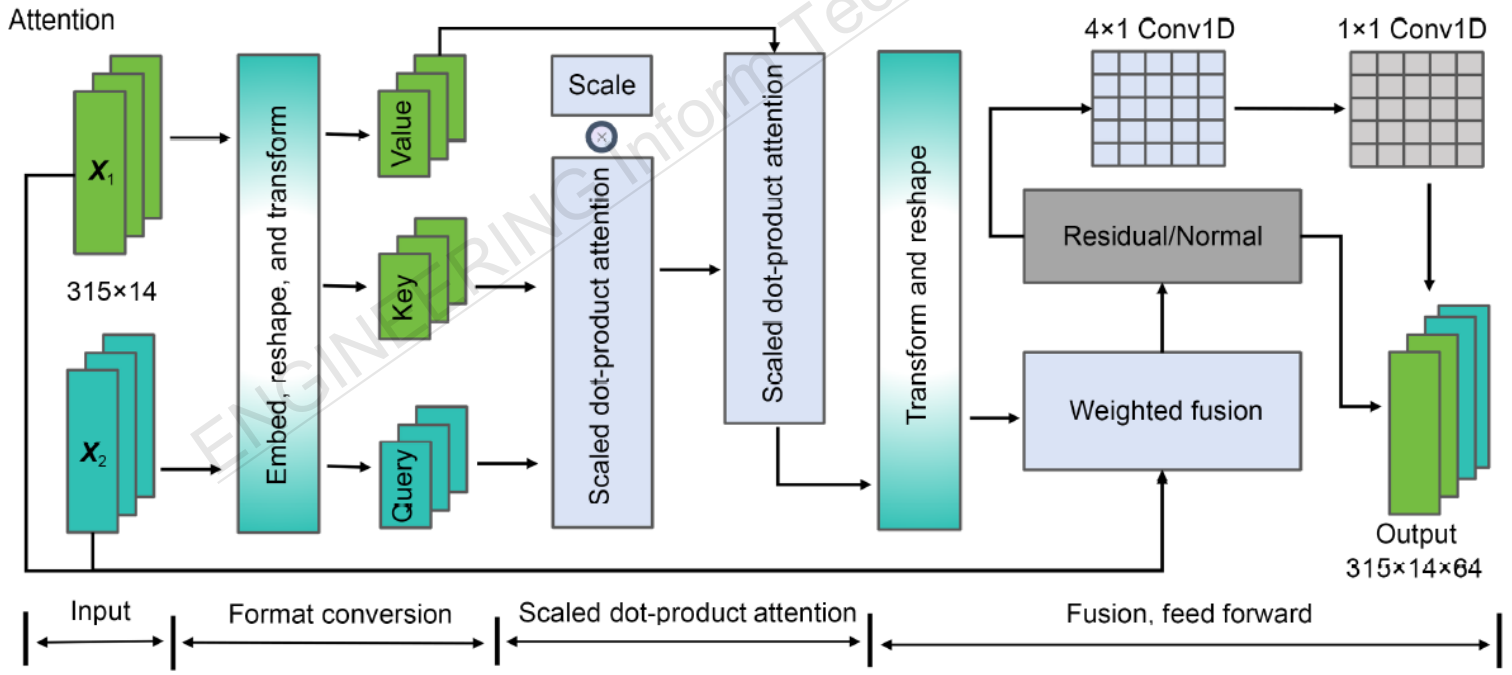

Fig. 3 Structure of cross-attention

Method (Cont'd)

4. The fused representations are passed to a hierarchical LSTM decoder. Comprising three stacked LSTM layers with residual connections, this decoder extracts deep temporal features. Finally, a hybrid pooling operation combines average and max pooling to generate a precise tool wear prediction.

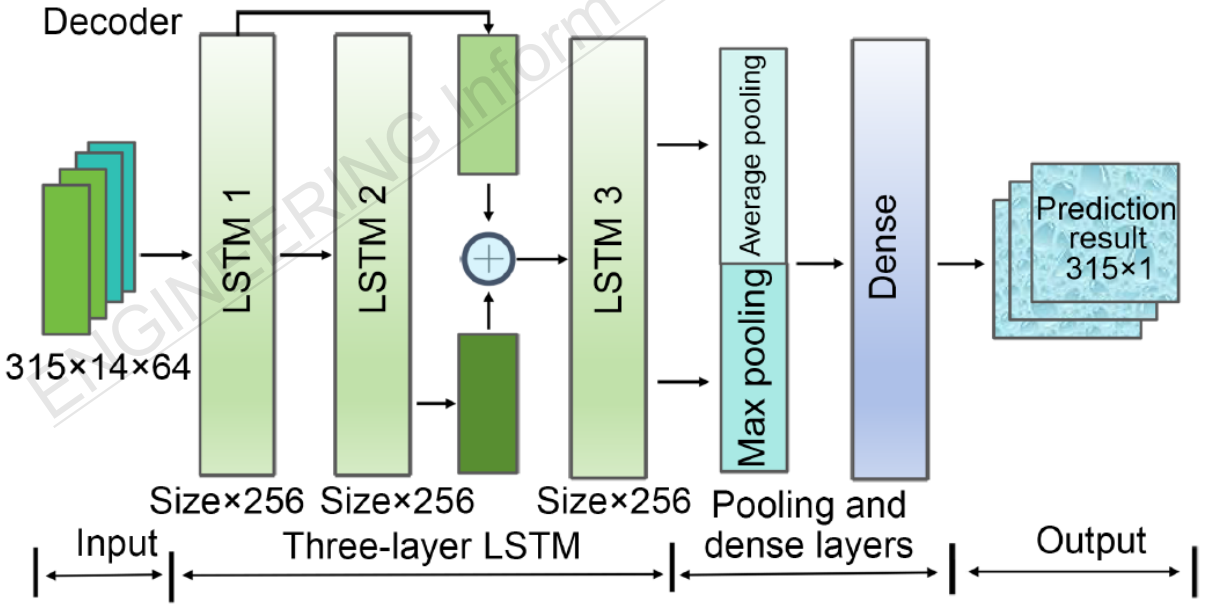

Fig. 4 Structure of the hierarchical decoder

Major results

Prediction performance

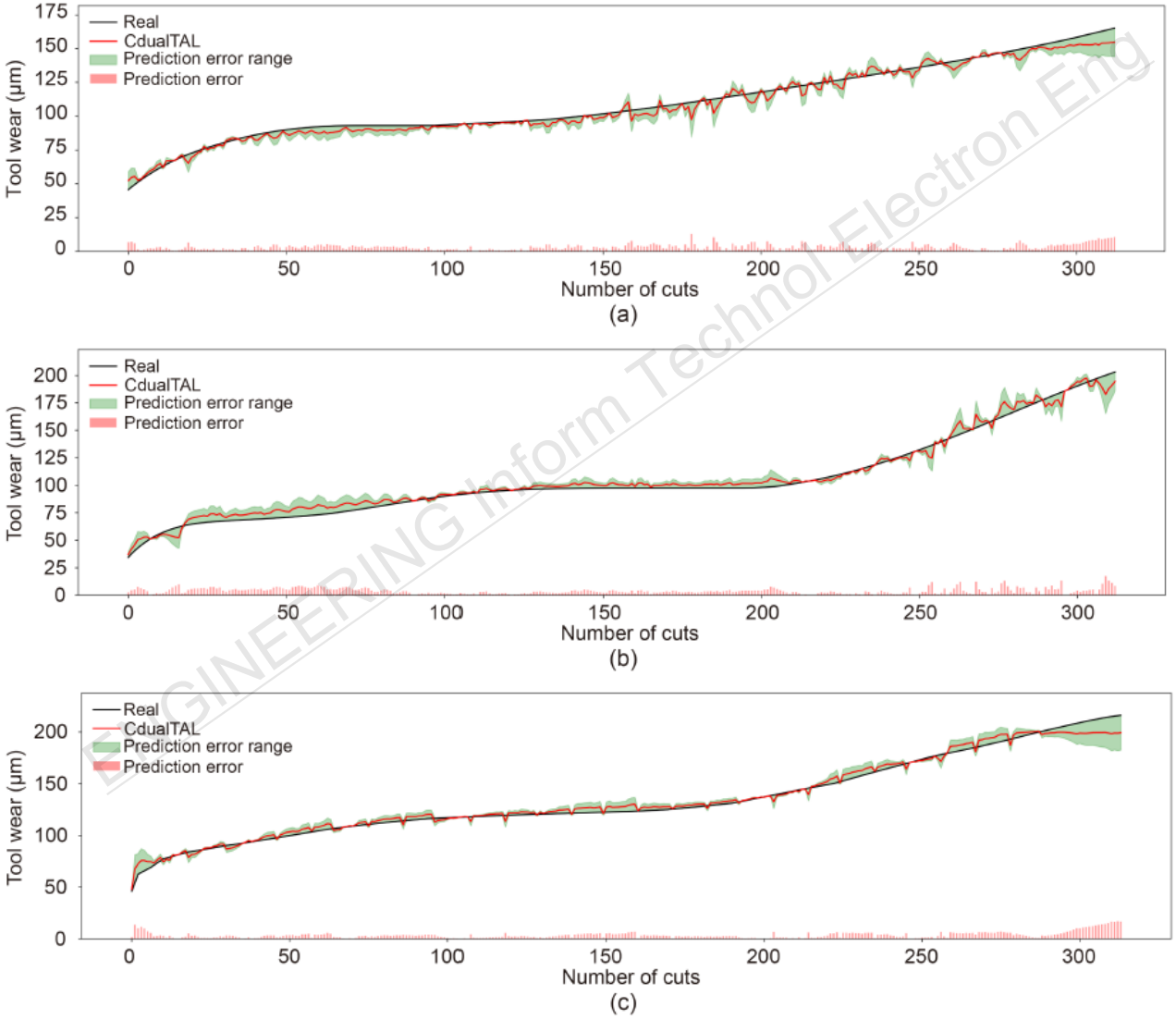

Fig. 7 Prediction results with error bar of CdualTAL: (a) C1 tool; (b) C4 tool; (c) C6 tool

Major results (Cont'd)

Ablation study

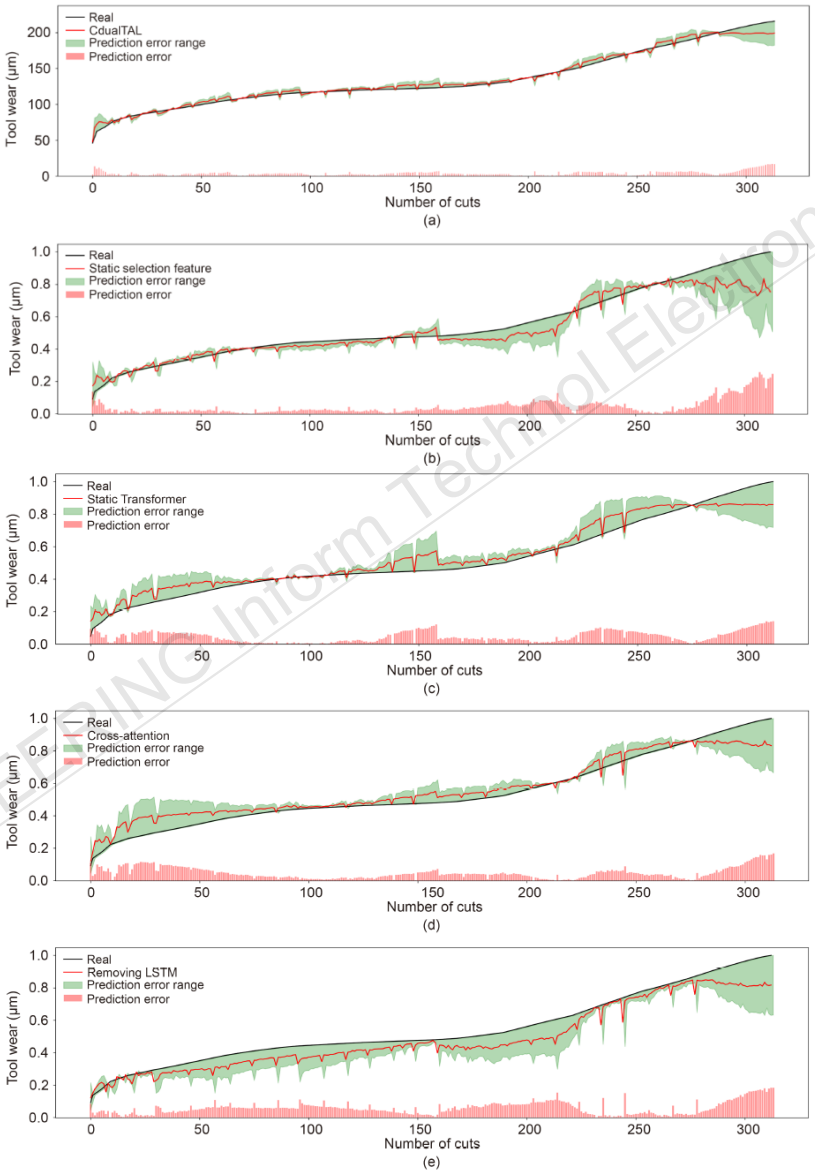

Fig. 8 Prediction results with error bars of different models: (a) CdualTAL model; (b) static selection; (c) removing Transformer; (d) cross-attention; (e) removing LSTM

Conclusions

1. CdualTAL establishes a new heterogeneous paradigm for industrial monitoring by synergistically combining feature isolation, adaptive fusion, and hierarchical decoding.

2. The adaptive feature selection and dual-channel encoder successfully isolate high-predictivity features to ensure robustness against sensor drift and noise.

3. Validation on Prognostics and Health Management (PHM) datasets confirms state-of-the-art performance with an average R^2 of 0.983, providing a precise solution for multi-domain tool wear monitoring.

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