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High-precision temperature prediction for atmospheric refractivity correction using Kalman spatiotemporal data fusion

Key words: Temperature prediction; Kalman filter expanded fusion (KFEF); Atmospheric refraction correction; Absolute distance measurement; Generalized regression neural network (GRNN) optimization

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Motivation

1. Atmospheric refraction error is the key limiting factor for high-precision absolute distance measurement and positioning. Temperature plays a dominant role in computing the atmospheric refractive index.

2. In complex and dynamic outdoor environments, limited sensor deployment and environmental nonstationarity make it extremely difficult to obtain accurate temperature fields along the ranging path.

Main idea

1. Propose Kalman filter expanded fusion (KFEF) algorithm for high-precision temperature prediction in atmospheric refractivity correction.

2. Integrate the advantages of generalized regression neural network (GRNN) (temporal prediction) and Kriging (spatial interpolation) based on the Kalman filter framework.

3. Achieve dynamic prediction and high-accuracy reconstruction of spatiotemporal temperature fields, adapting to sparse sensors and complex outdoor environments.

KFEF method

1. Dynamic GRNN optimization algorithm based on simulated annealing (GRNN-SA): Proposes a simulated annealing-based optimization strategy for GRNN smoothing factor selection.

2. Adaptive Kalman filtering with spatial correlation modeling: Constructs a state transition matrix using Kriging variogram theory and dynamically updates measurement noise covariance through GRNN prediction residuals.

3. Fixed-interval interpolation enhancement: Introduces a data augmentation strategy that combines GRNN prediction and Kriging interpolation to expand sparse sensor observations.

Major results

1. Test results of our model and related methods in simulations

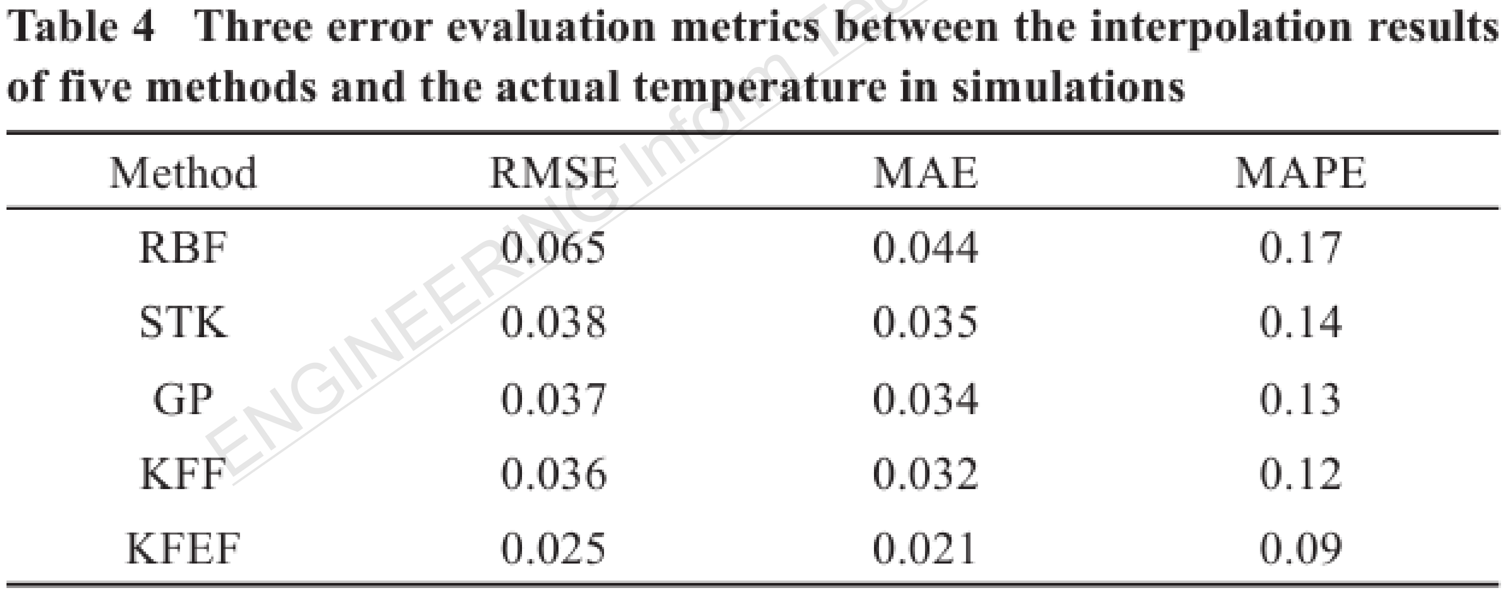

Table 4 Three error evaluation metrics between the interpolation results of five methods and the actual temperature in simulations

Method	RMSE	MAE	MAPE
RBF	0.065	0.044	0.17
STK	0.038	0.035	0.14
GP	0.037	0.034	0.13
KFF	0.036	0.032	0.12
KFEF	0.025	0.021	0.09

Major results (Cont’d)

2. Test results of our model and related methods in the indoor experiment

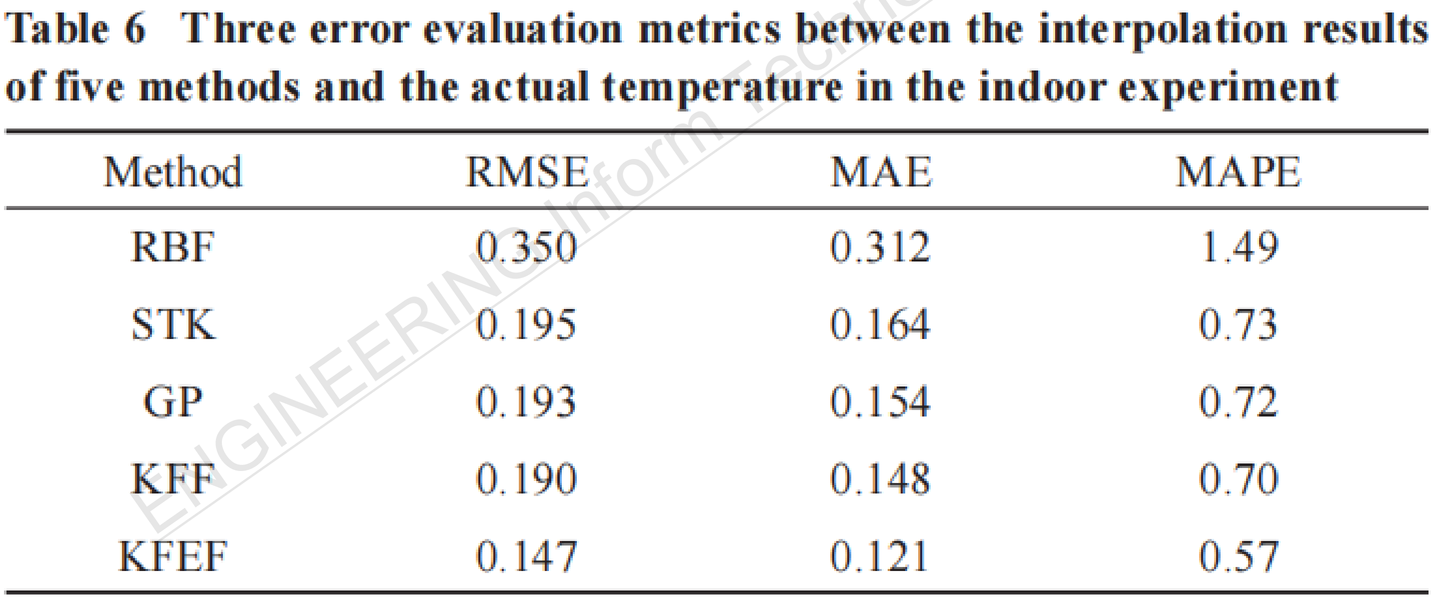

Table 6 Three error evaluation metrics between the interpolation results of five methods and the actual temperature in the indoor experiment

Method	RMSE	MAE	MAPE
RBF	0.350	0.312	1.49
STK	0.195	0.164	0.73
GP	0.193	0.154	0.72
KFF	0.190	0.148	0.70
KFEF	0.147	0.121	0.57

Major results (Cont'd)

3. Test results of our model and related methods in the outdoor experiment

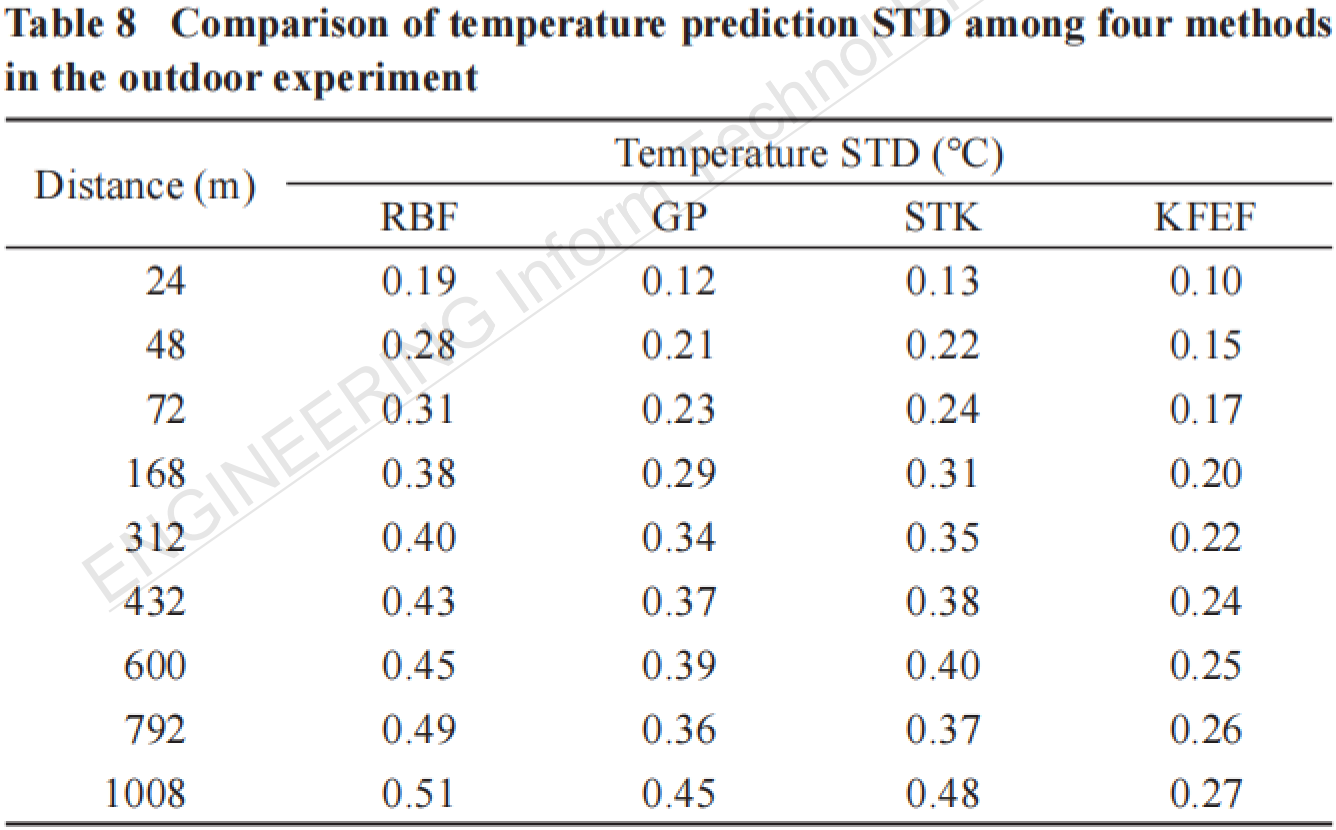

Table 8 Comparison of temperature prediction STD among four methods in the outdoor experiment

Distance (m)	Temperature STD (℃)			
	RBF	GP	STK	KFEF
24	0.19	0.12	0.13	0.10
48	0.28	0.21	0.22	0.15
72	0.31	0.23	0.24	0.17
168	0.38	0.29	0.31	0.20
312	0.40	0.34	0.35	0.22
432	0.43	0.37	0.38	0.24
600	0.45	0.39	0.40	0.25
792	0.49	0.36	0.37	0.26
1008	0.51	0.45	0.48	0.27

Conclusions

1. We propose KFEF algorithm integrating GRNN-SA, Kriging interpolation, and adaptive Kalman filter for atmospheric refractivity correction under sparse sensor observations.

2. Simulations verify that KFEF achieves a 61.54% reduction in root mean square error (RMSE) compared with the radial basis function (RBF). KFEF lowers the microwave ranging error from millimeter to micrometer level for kilometer-scale ranging in the outdoor experiment.

3. The spatiotemporal fusion framework is general and scalable for various temperature field tasks, and future work will enhance its adaptability to nonstationary atmospheric environments.

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