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Long working distance portable smartphone microscopy for metallic mesh defect detection

Key words: Smartphone microscope; Defect detection; Reflective portable imaging; Metallic mesh; Low-rank decomposition

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Motivation

1. Transparent electromagnetic shielding films like metallic meshes currently rely on manual inspection, which is inefficient and error-prone. While smartphone microscopes offer portability, their short working distances and transmission-mode designs limit industrial applicability. A reflective system with an extended working distance is urgently needed.

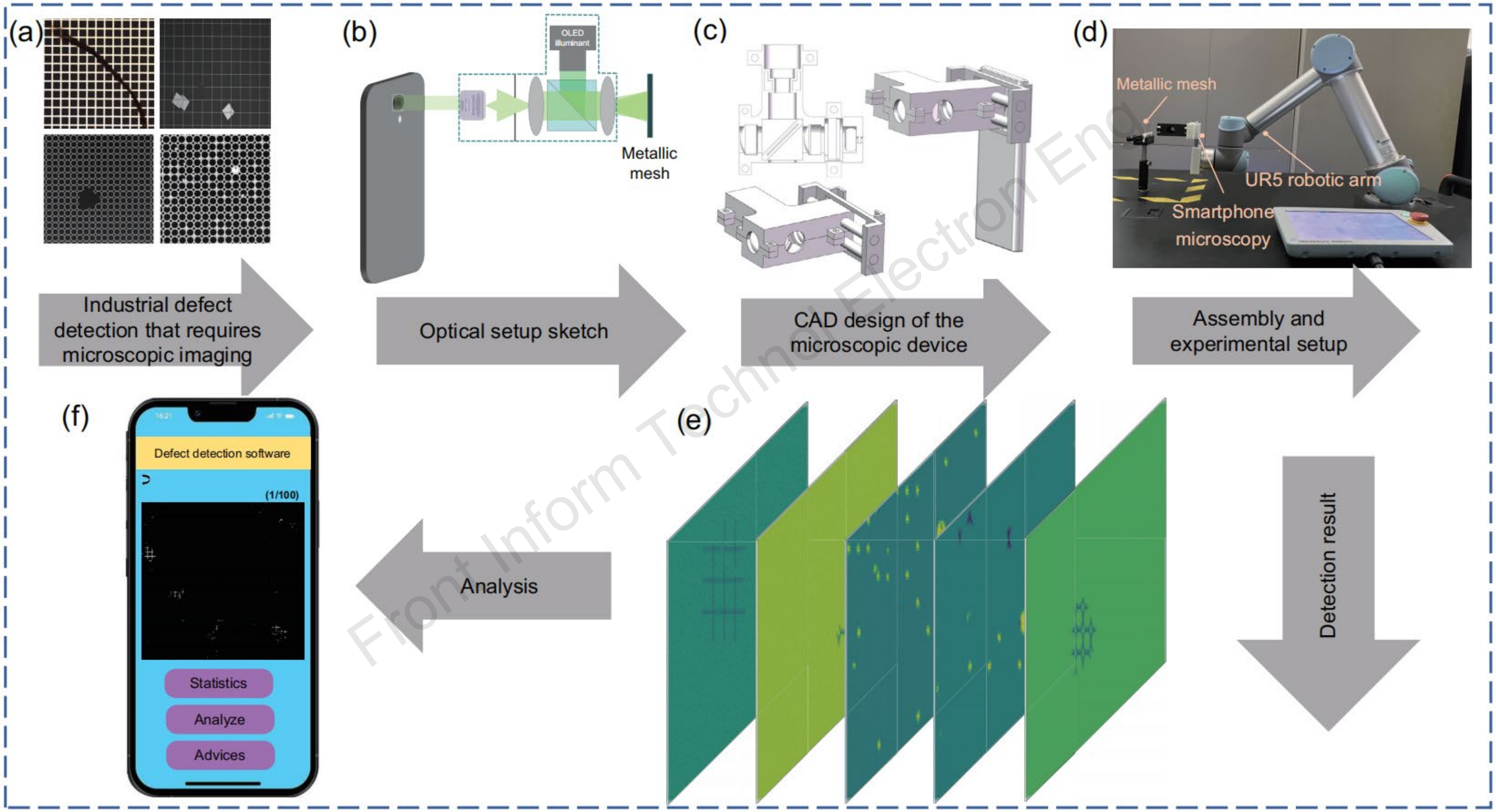
2. Defect detection in metallic meshes faces challenges from their periodic textures and diverse defect types. Existing approaches, including spectral analysis, deep learning, and low-rank decomposition, have limitations in accuracy or efficiency. An optimized algorithm incorporating structural priors could enable reliable real-time detection.

Main idea

1. We propose a novel reflective smartphone microscopy system (LD-RSM) with an extended working distance, overcoming the transmission-mode limitations of existing devices, and integrate it with a robotic arm to achieve comprehensive large-area scanning for industrial defect detection.

2. We develop a dual-prior weighted low-rank decomposition model (DW-RPCA) that innovatively integrates spectral filter fusion and the Hough transform to address the unique challenges of defect detection in periodic metallic mesh structures, achieving superior detection accuracy.

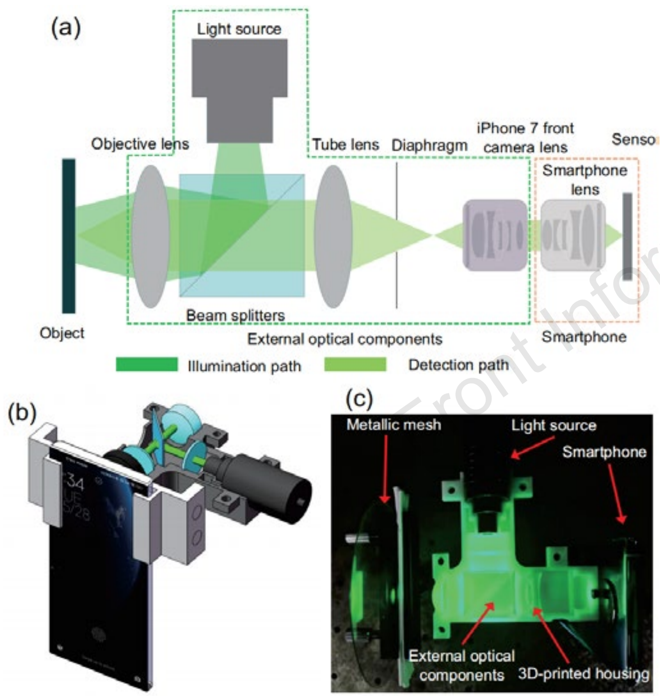
Framework



Schematic of the rapid prototyping of the LD-RSM system

Method

1. We develop a long working distance reflective imaging system using a 4*f* optical design with smartphone microscopy, featuring a dedicated scanning solution for large-area inspection.



Design and fabrication of the LD-RSM system

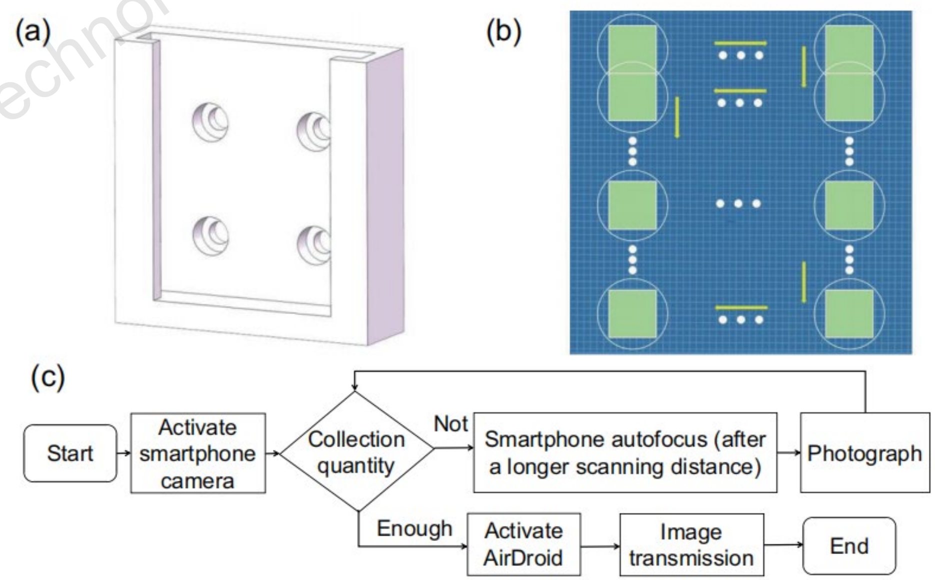
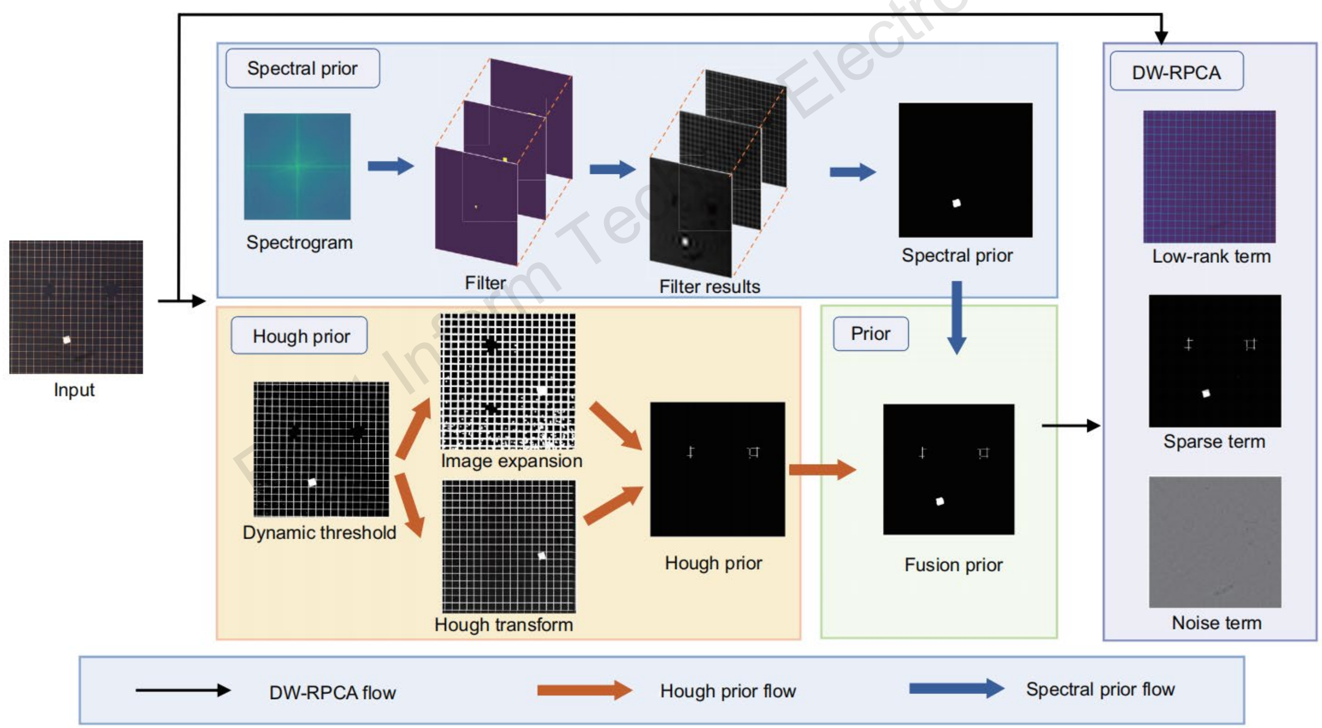


Image acquisition and transmission strategies

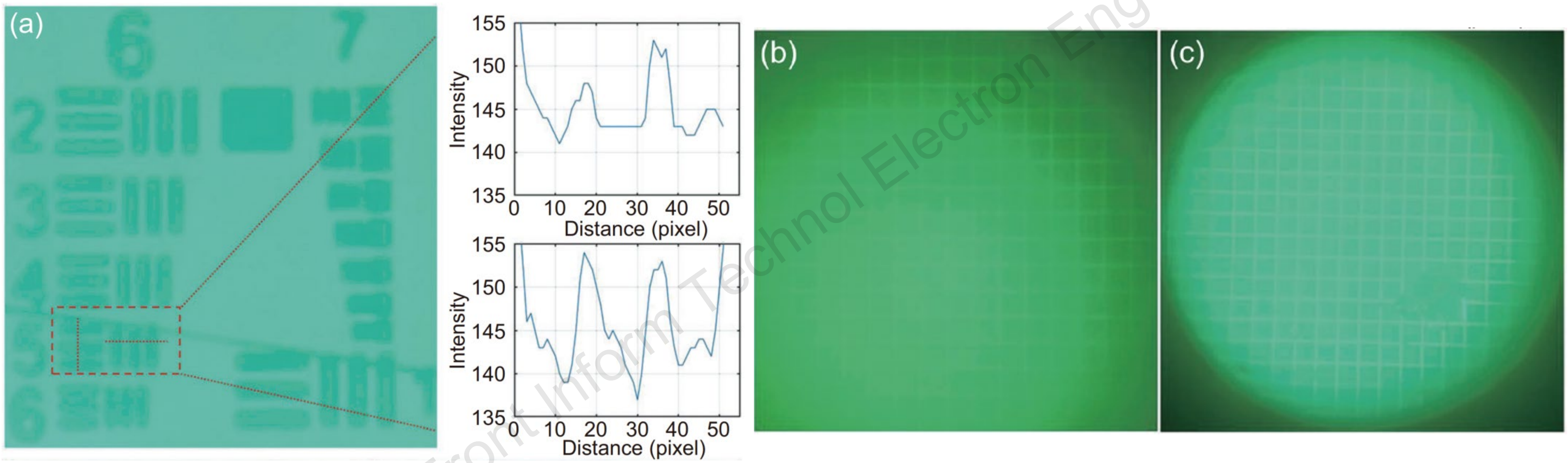
Method

2. To enhance detection accuracy, we develop a low-rank decomposition model incorporating the Hough transform and spectral fusion for defect detection in both square and circular metallic mesh.



Overall dual-prior weighted robust principal component analysis (DW-RPCA) detection process

Major results



Characterization of the LD-RSM system: (a) image of a USAF-1951 resolution test target acquired by LD-RSM; (b) imaging result before improvement; (c) imaging result after the measures to suppress stray light

Major results

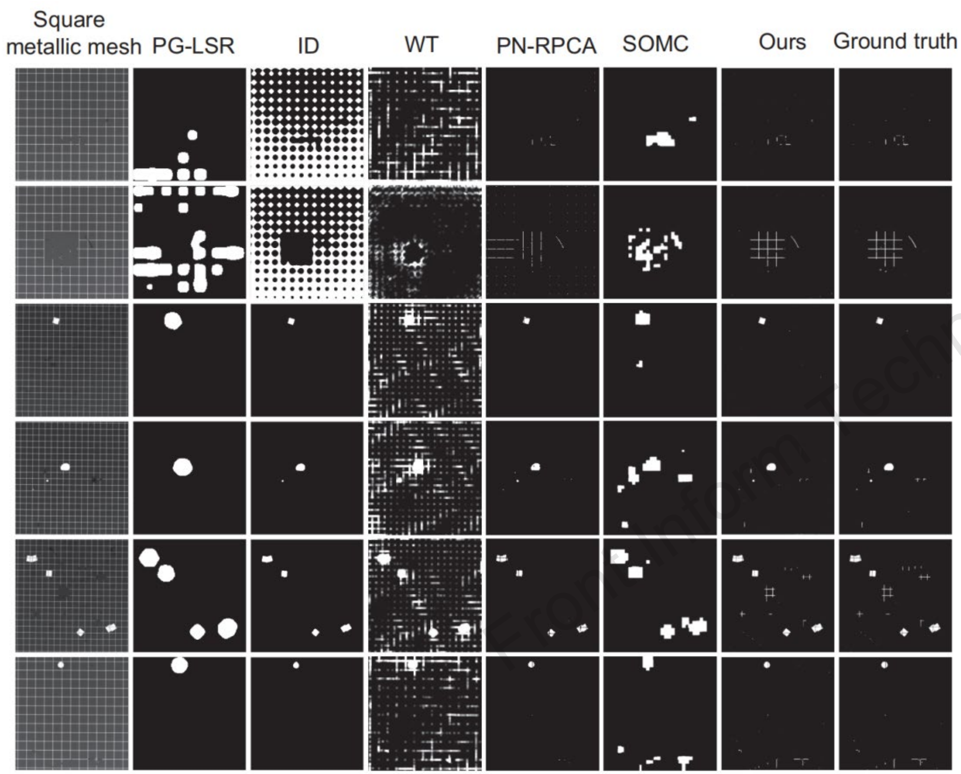


Table 1 Quantitative comparisons of the square metallic mesh dataset

Defect	TPR	FPR	PPV	NPV	f	Method
Broken	0.3909	0.1565	0.0086	0.9966	0.0168	PG-LSR
	0.1821	0.4680	0.0009	0.9939	0.0019	ID
	0.3413	0.2579	0.0046	0.9956	0.0091	WT
	0.5097	0.0011	0.7423	0.9974	0.6009	PN-RPCA
	0.6905	0.0298	0.0730	0.9980	0.1274	SOMC
	0.8158	**0.0003**	**0.8860**	**0.9995**	**0.8480**	Ours
Block	0.9227	0.0237	0.1372	**0.9997**	0.2356	PG-LSR
	0.8667	0.0445	0.8148	0.9994	0.8023	ID
	0.9456	0.2592	0.0172	**0.9997**	0.0334	WT
	0.7768	**0.0001**	**0.9892**	0.9989	0.8651	PN-RPCA
	0.9713	0.0252	0.1429	0.9995	0.2464	SOMC
	0.8772	0.0004	0.8769	0.9995	**0.8753**	Ours
Mixed	0.5720	0.0365	0.1142	0.9972	0.1886	PG-LSR
	0.5388	0.0918	0.7114	0.9963	0.5783	ID
	0.5750	0.2441	0.0218	0.9950	0.0412	WT
	0.3667	**0.0001**	**0.9841**	0.9943	0.5174	PN-RPCA
	0.8605	0.0441	0.1423	0.9986	0.2414	SOMC
	0.8157	0.0006	0.8815	**0.9989**	**0.8460**	Ours

The best results are in bold

Visual and quantitative comparisons with five baseline methods on the square metallic mesh dataset

Major results

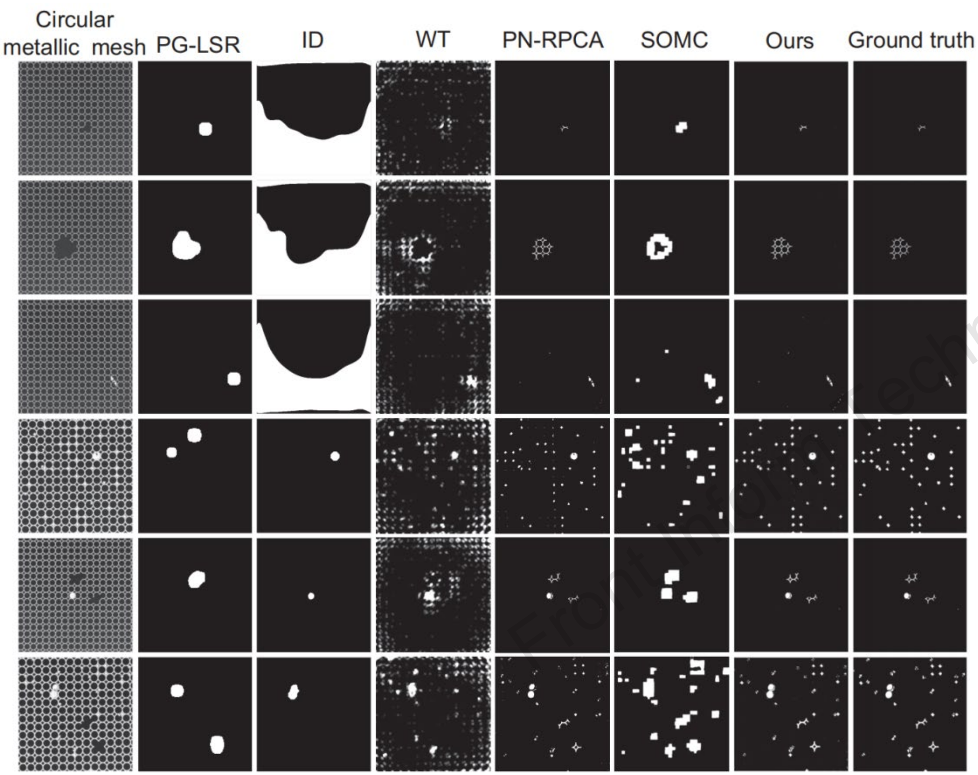


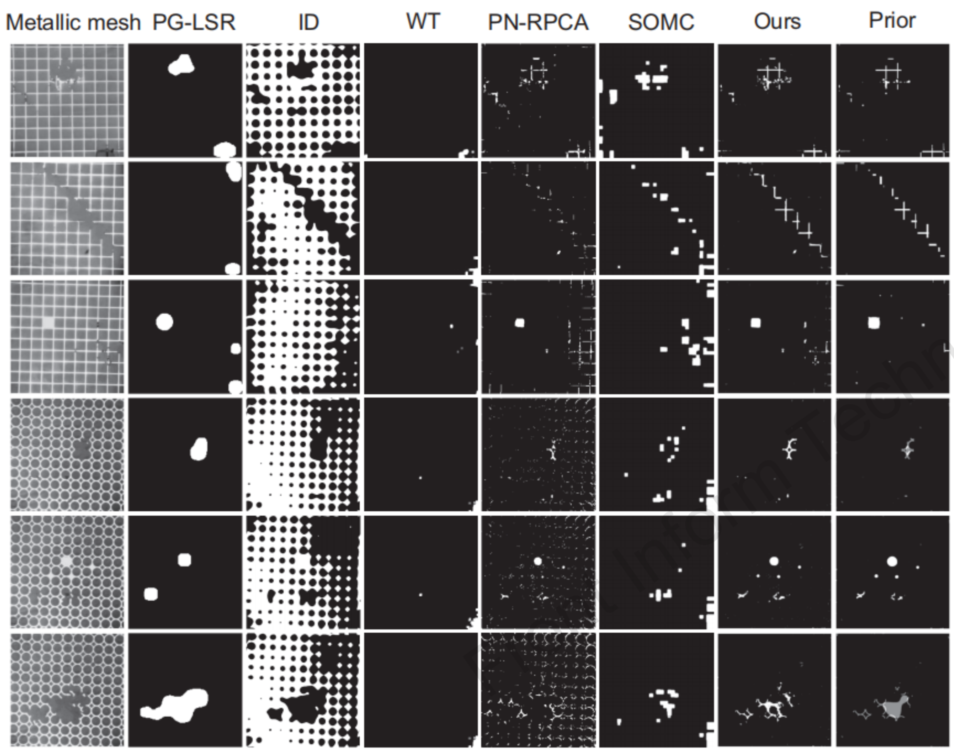
Table 2 Quantitative comparisons of the circular metallic mesh dataset

Defect	TPR	FPR	PPV	NPV	f	Method
	0.6159	0.0246	0.0539	0.9996	0.0983	PG-LSR
	0.1821	0.4680	0.0009	0.9939	0.0019	ID
Broken	0.2466	0.1985	0.0049	0.9980	0.0096	WT
	0.4469	**0.0001**	**0.9382**	0.9975	0.6035	PN-RPCA
	0.9008	0.0219	0.1508	0.9993	0.2537	SOMC
	0.9564	0.0004	0.8089	**0.9998**	**0.8716**	Ours
	0.3350	0.0333	0.1110	0.9908	0.1360	PG-LSR
	0.8667	0.0445	0.8148	**0.9994**	0.8023	ID
Block	**0.9629**	0.2131	0.0512	0.9993	0.0948	WT
	0.6079	0.0066	**0.8365**	0.9946	0.6566	PN-RPCA
	0.7352	0.0414	0.1496	0.9958	0.2446	SOMC
	0.8479	**0.0019**	0.8095	0.9977	**0.8288**	Ours
	0.3015	0.0225	0.1294	0.9878	0.1618	PG-LSR
	0.5388	0.0918	0.7114	0.9963	0.5783	ID
Mixed	0.6424	0.2013	0.0815	0.9890	0.1409	WT
	0.3821	0.0069	**0.8526**	0.9832	0.5027	PN-RPCA
	0.7014	0.0586	0.2194	0.9897	0.3277	SOMC
	0.8514	**0.0025**	0.8489	**0.9974**	**0.8496**	Ours

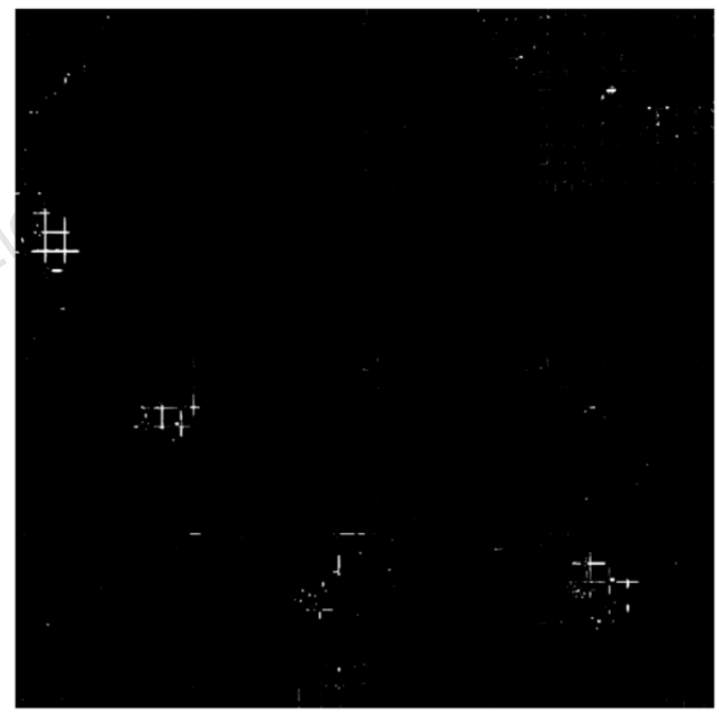
The best results are in bold

Visual and quantitative comparisons with five baseline methods on the circular metallic mesh dataset

Major results



Acquired images of square metallic mesh and circular metallic mesh with the comparison of multiple defect detection results



Results of large metallic mesh (2 mm × 2 mm) defect detection

Conclusions

1. We present a long working distance reflective smartphone microscope (LD-RSM) with a 22.23 mm working distance and a 4.92 μm resolution, overcoming the limitations of conventional smartphone microscopes for industrial inspection.

2. We develop a dual-prior weighted RPCA (DW-RPCA) algorithm integrating spectral filter fusion and the Hough transform, achieving an *f*-value accuracy of 0.856 in metallic mesh defect detection.

3. The combined LD-RSM and DW-RPCA system enables comprehensive in situ defect inspection of large-area metallic meshes, offering a portable yet precise solution for industrial quality control.

Zhengang LU received his BS and PhD degrees in instrument science and technology from Harbin Institute of Technology (HIT), Harbin, China. At present, he is a professor and vice director of the Center of Ultra-precision Optoelectronic Instrument Engineering, HIT. He is also a corresponding expert of *Front Inform Technol Electron Eng*. His current research interests include micro-nano optics, electromagnetic shielding optical windows, and precision instruments and engineering.

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