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Multi-aperture optical imaging systems and their mathematical light field acquisition models

Key words: Multi-aperture optical imaging system; Artificial compound eye; Light field camera; Camera array; Light field acquisition model

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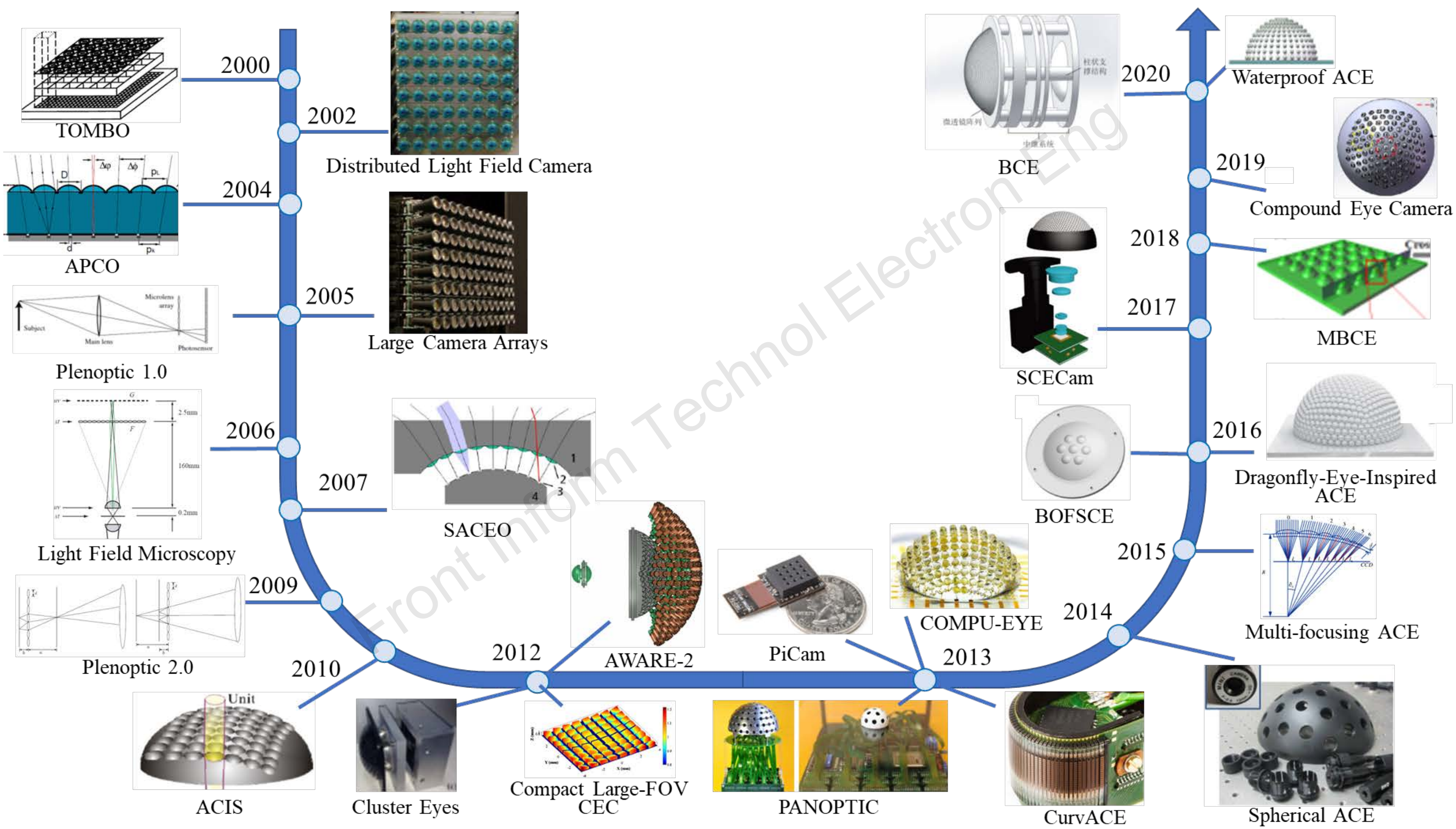
Motivation

1. Multi-aperture optical imaging systems integrate preparation technology, optical design, and machine vision algorithms, and they have great value in applications such as reconnaissance, image navigation, computational photography, and medical endoscopy.

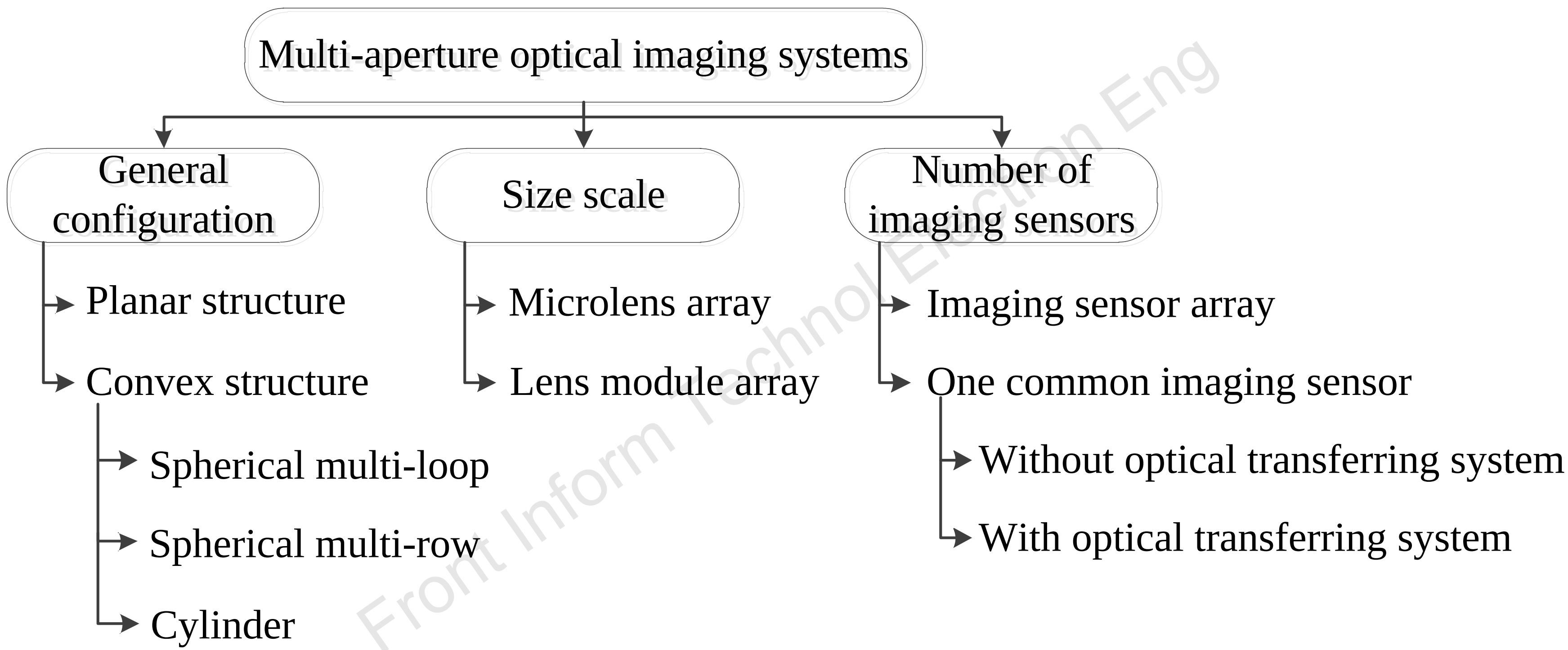
2. Mathematical light field acquisition models play an essential role in closing the gap between configuration design and application research. However, there is little research that summarizes light field acquisition for multi-aperture optical imaging systems from a genralized mathmatical view.

Typical multi-aperture optical imaging systems



The development trend of multi-aperture optical imaging systems

Typical multi-aperture optical imaging systems



The classification of multi-aperture optical imaging systems

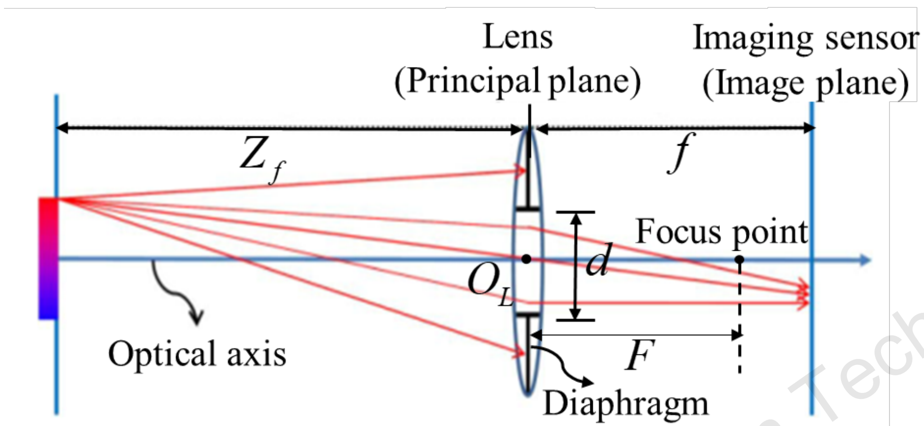
Typical multi-aperture optical imaging systems

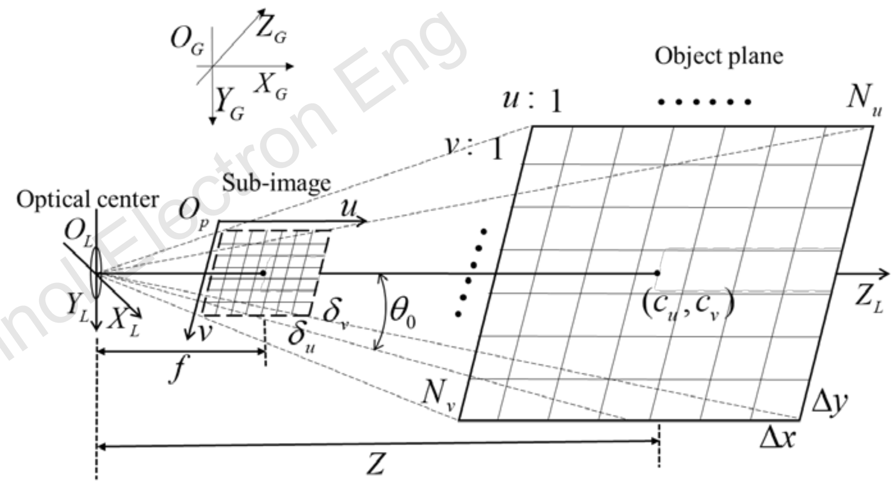
Table 1 The features of typical multi-aperture optical imaging systems

Name	General configuration	Size scale	Number of imaging sensors
TOMBO (Tanida et al., 2000)	1	1	2(1)
Distributed light field camera (Yang JC et al., 2002)	1	2	1
APCO (Duparré et al., 2005)	1	1	1
Plenoptic 1.0 (Ng and Hanrahan, 2005)	1	1	2(1)
Large camera arrays (Wilburn et al., 2005)	1	2	1
Light field microscopy (Levoy et al., 2006)	1	1	2(1)
SACEO (Duparré et al., 2007)	2(–)	1	2(2)
Plenoptic 2.0 (Lumsdaine and Georgiev, 2009)	1	1	2(1)
ACIS (Zhang YK et al., 2010)	2(2)	1	1
Cluster eyes (Guo et al., 2012)	2(1)	2	2(2)
AWARE-2 (Brady et al., 2012)	2(1)	2	1
PANOPTIC (Afshari et al., 2013)	2(1)	2	1
Compact large-FOV CEC (Li and Yi, 2012)	1	1	2(1)
PiCam (Venkataraman et al., 2013)	1	2	1
COMPU-EYE (Song et al., 2013)	2(2)	1	1
CurvACE (Leitel et al., 2014)	2(3)	1	1
Spherical ACE (Cao et al., 2015)	2(1)	2	1
Multi-focusing ACE (Luo et al., 2015)	2(1)	1	2(1)
Dragonfly-eye-inspired ACE (Deng et al., 2016)	2(2)	1	–
BOFSCE (Pang et al., 2017)	2(1)	1	2(1)
SCECam (Shi et al., 2017)	2(1)	1	2(2)
MBCE (Cao et al., 2018)	1	1	–
Compound eye camera (Yu et al., 2019)	2(1)	2	2(2)
BCE (Zhang JM et al., 2020)	2(1)	1	2(2)
Waterproof ACE (Zhou et al., 2020)	2(1)	1	–

In the 2nd column: 1, planar structure; 2(1/2/3), convex structure (sphere multi-loop/sphere multi-row/cylinder). In the 3rd column: 1, microlens array; 2, lens module array. In the 4th column: 1, imaging sensor array; 2(1/2), one common imaging sensor (without/with optical transferring system). –: not clear

Single-aperture optical imaging model





Single-aperture optical path model

⇩

Physical level

This model is used to analyze the imaging quality.

Pinhole model

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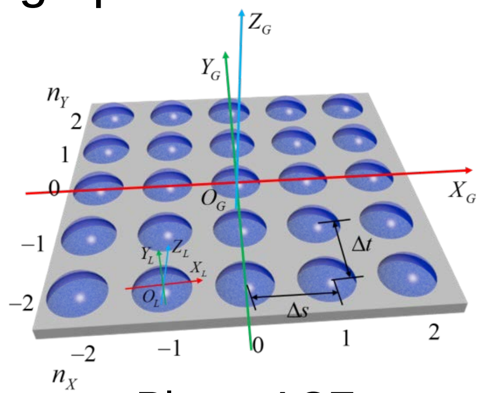
Mathematical level

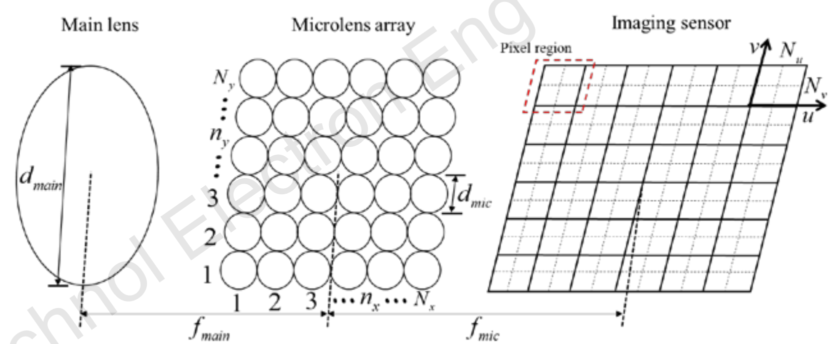
The model is used for machine vision applications.

Light field acquisition models for different configurations

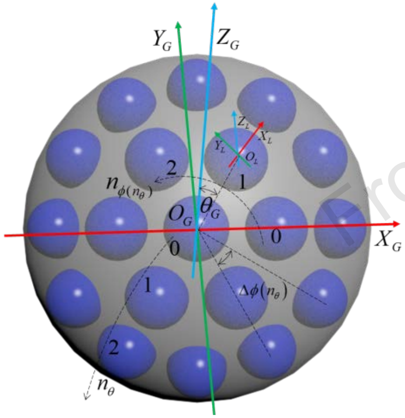
1. The characteristics of each configuration and the pose relation between imaging apertures are analyzed.



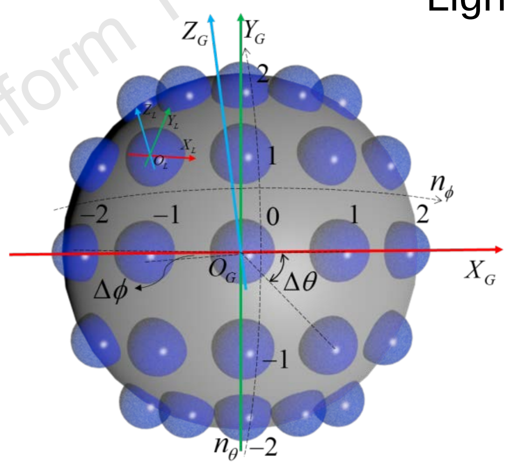
Planar ACE



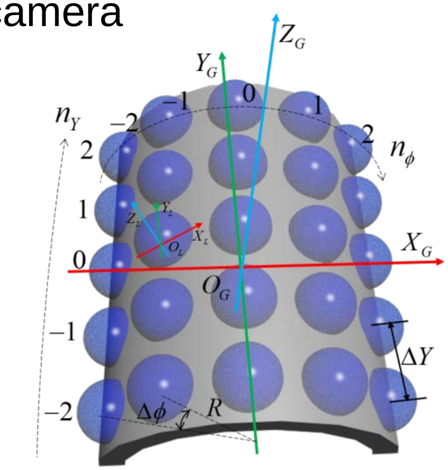
Light field camera



Convex ACE in spherical multi-loop arrangement



Convex ACE in spherical multi-row arrangement

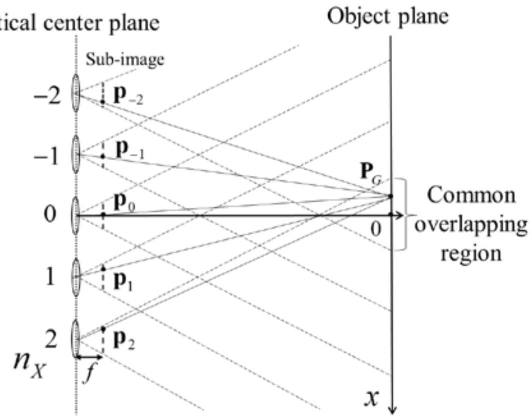


Convex ACE in cylinder arrangement

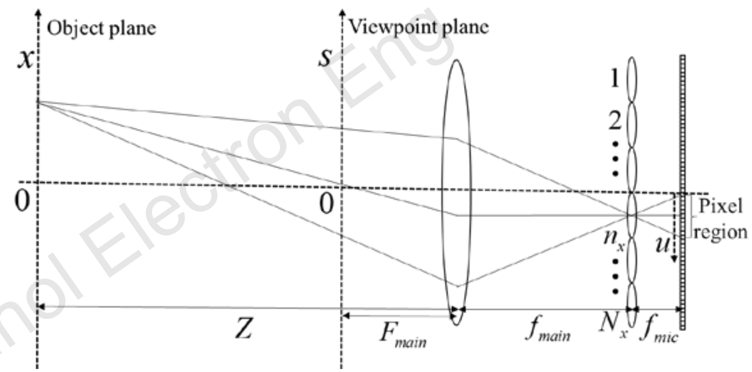
Typical configurations of multi-aperture optical imaging systems

Light field acquisition models for different configurations

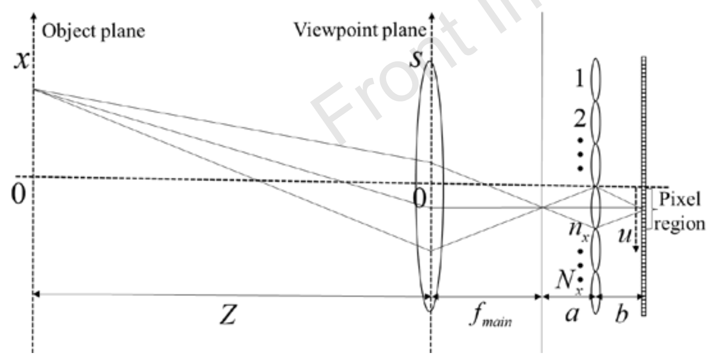
2. The light field acquisition model is deduced for each configuration.



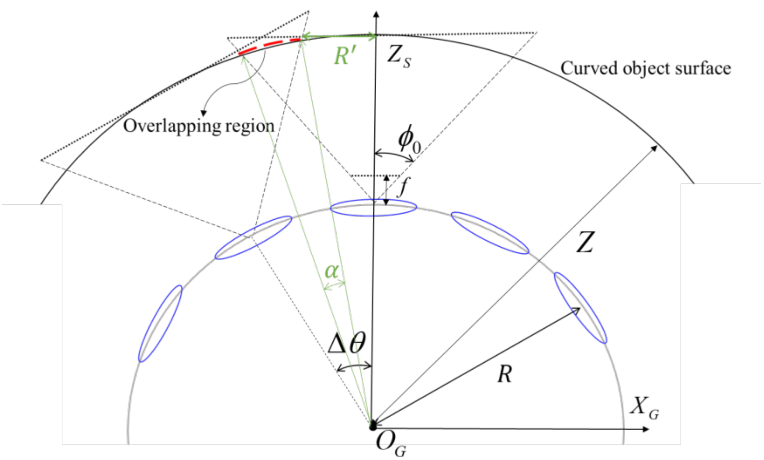
Planar ACE



Plenoptic 1.0



Plenoptic 2.0



Convex ACE

Schematic of light field acquisition

Light field acquisition models for different configurations

3. The imaging performance is quantitatively analyzed based on the light field acquisition model.

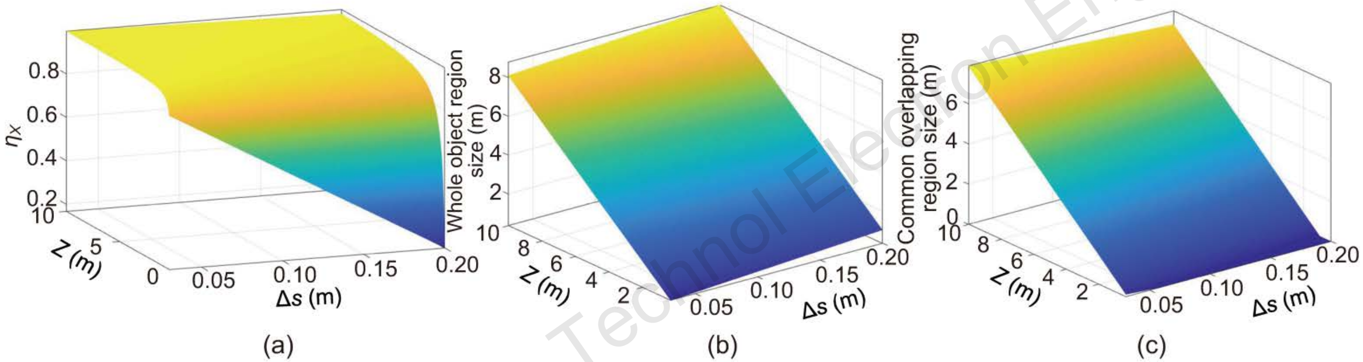


Fig. 7 Quantitative analysis: (a) variation trend of η_X; (b) variation trend of the whole object region size; (c) variation trend of the common overlapping region size

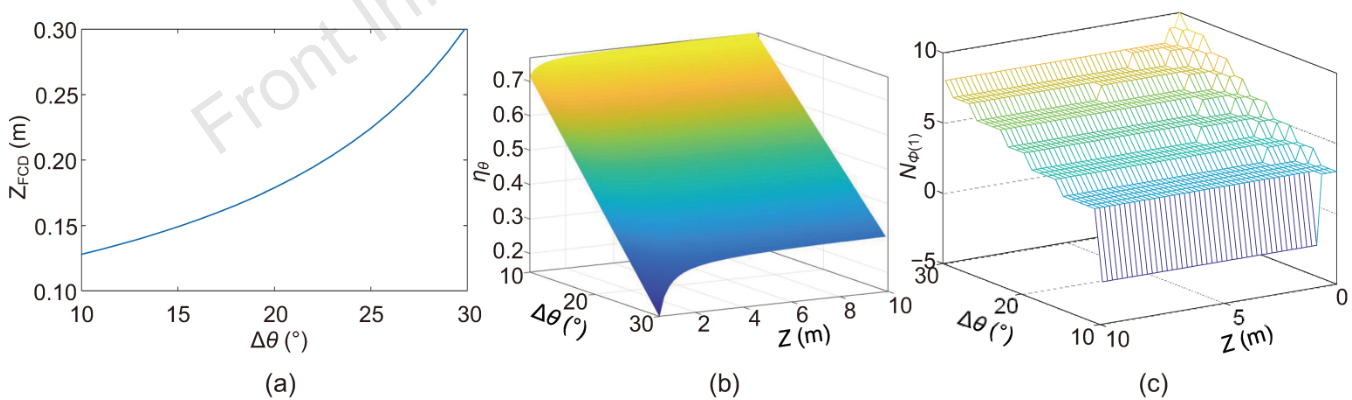


Fig. 15 Quantitative analysis: (a) variation trend of Z_{FCD} when $\Delta\theta$ varies; (b) variation trend of η_θ when $\Delta\theta$ and Z vary; (c) variation trend of $N_{\phi(1)}$ when $\Delta\theta$ and Z vary

Application analysis of multi-aperture optical imaging systems

1. Planar structure

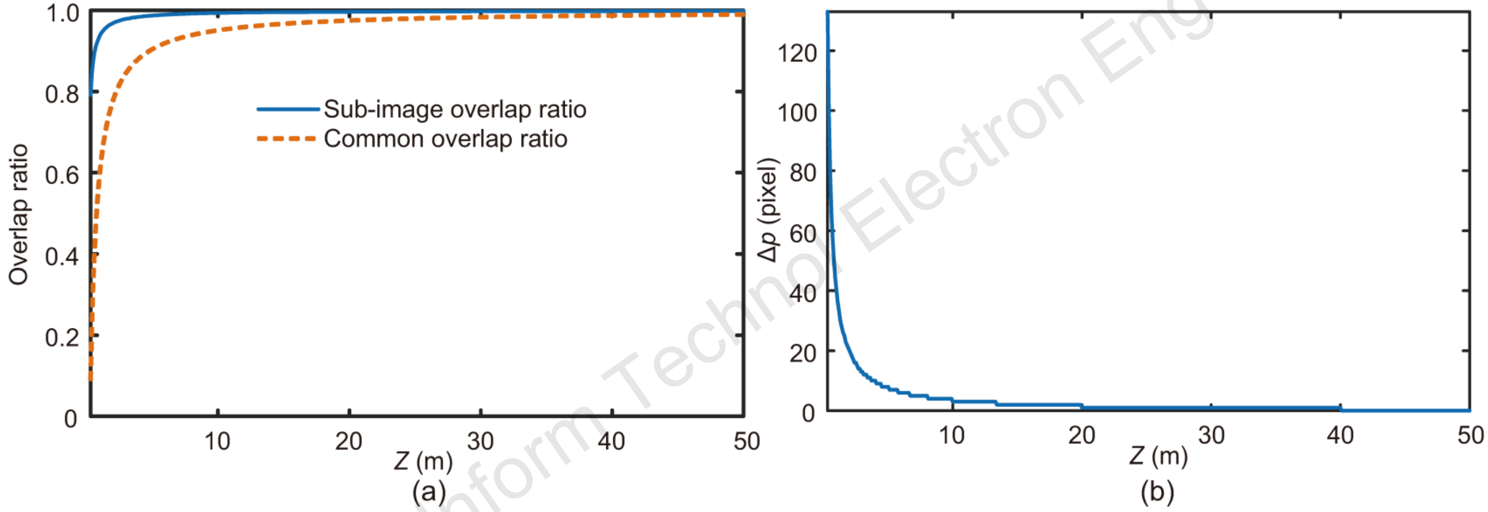


Fig. 18 The variation trend of the sub-image overlap ratio and common overlap ratio (a) and Δp (b)

When the scene depth is large enough, the FOV of each aperture almost completely overlaps, and a pixel region of the common overlapping field will have multiple subpixels, which is suitable for superresolution reconstruction.

Application analysis of multi-aperture optical imaging systems

1. Planar structure

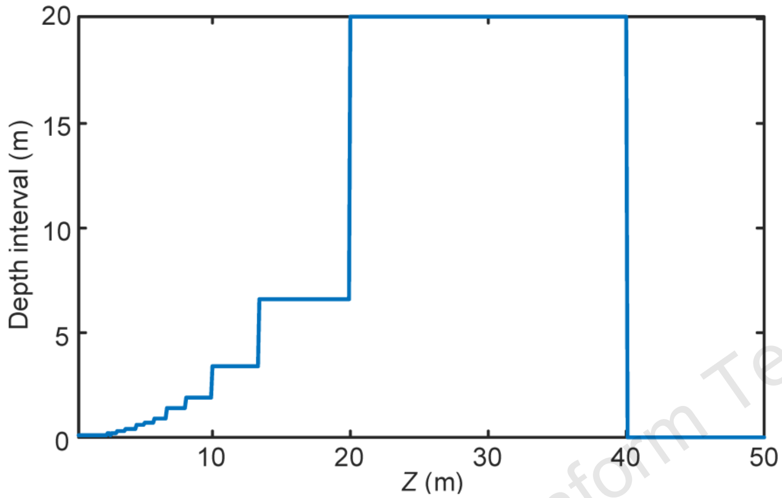


Fig. 19 The depth interval for Fig. 18b

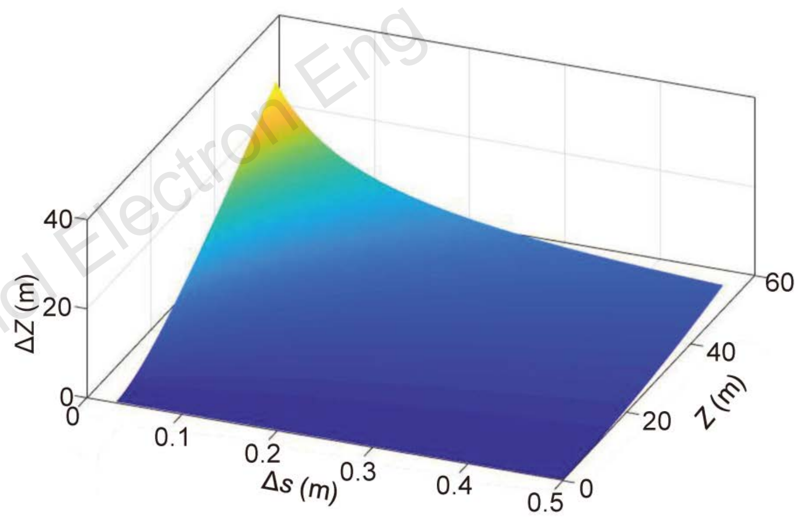


Fig. 20 The depth estimation accuracy

When the scene depth is not large, the parallax of adjacent apertures is visible and the stereo perception is excellent, suitable for light field refocusing as well as depth estimation.

Application analysis of multi-aperture optical imaging systems

2. Convex structure

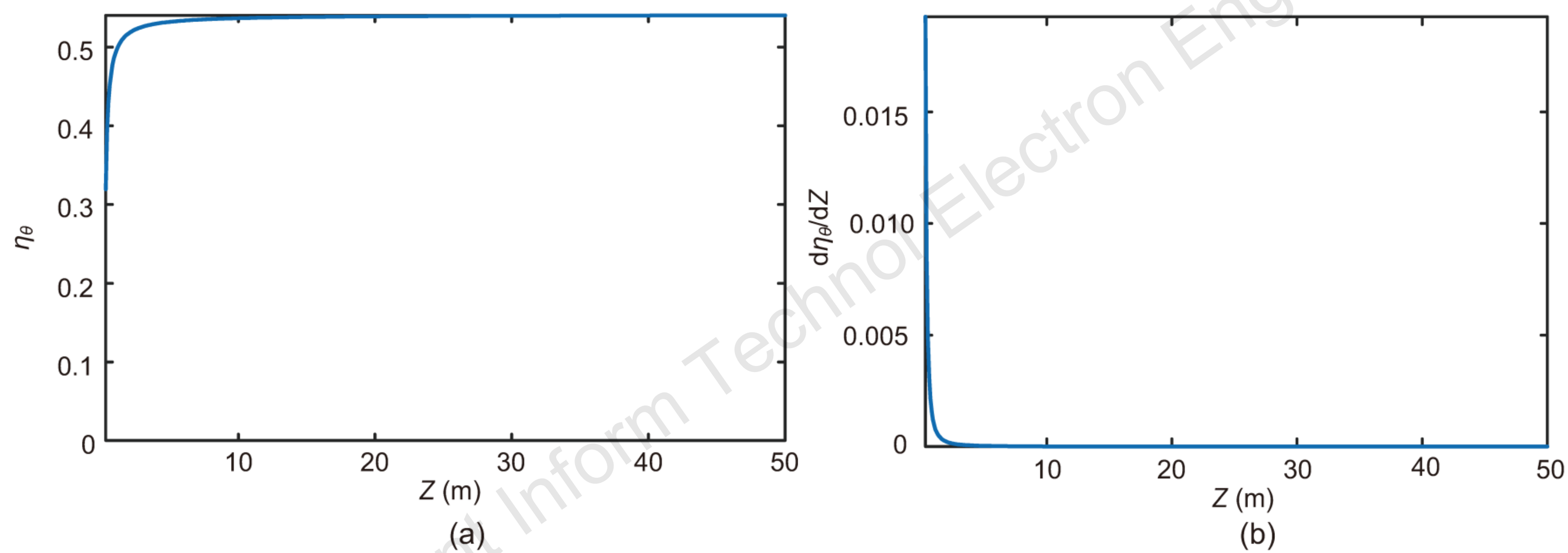


Fig. 21 The variation trend of η_θ (a) and $\mathrm{d}\eta_\theta/\mathrm{d}Z$ (b)

When the scene depth is large enough, the sub-image overlap ratio is approximately constant, so the non-overlapping parts of adjacent sub-images can be spliced proportionally.

Application analysis of multi-aperture optical imaging systems

2. Convex structure

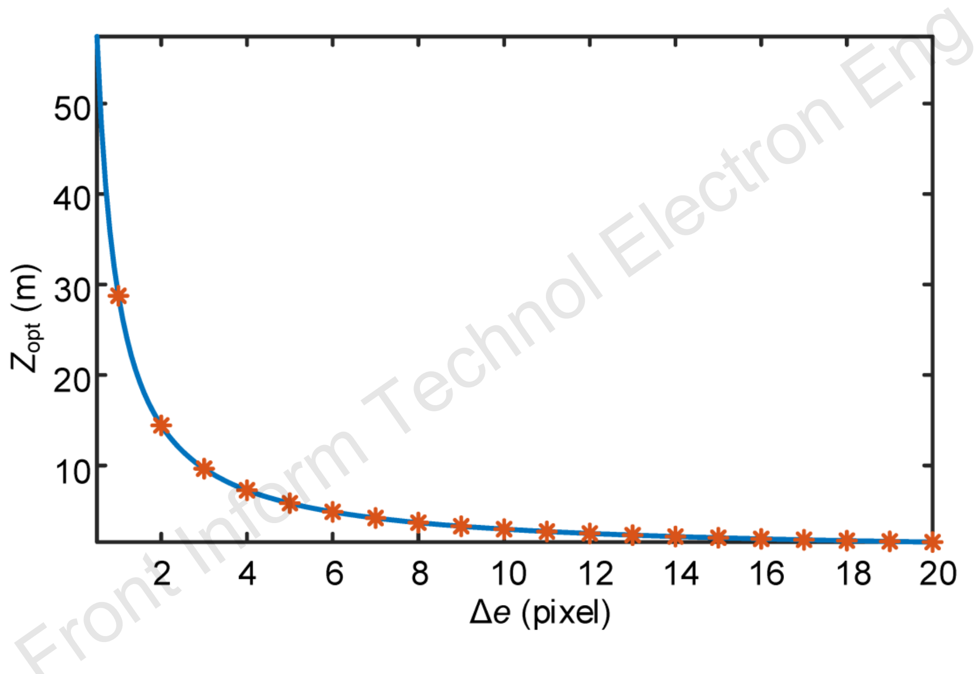


Fig. 22 The variation trend of Z_{opt} with Δe

The larger the scene depth, the more precise the segmented image stitching.

Conclusions and future work

1. Some typical multi-aperture optical imaging systems were enumerated and categorized. Then, the light field acquisition models were summarized according to their different structures. Based on mathematical models, the key indexes of different multi-aperture optical imaging systems can be computed easily.

2. In the future, multi-aperture optical imaging systems will be smaller and more flexible, and have higher resolution.

3. Multi-aperture optical imaging systems will be more widely used in the fields of computational photography, surveillance and reconnaissance, image navigation, 3D reconstruction, and so on.

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