Article ID:1004-4213(2011)11-1619-6

Space-based Telescope with Variable Resolution at Any Field Angle by Active Optical Zoom

XIE Yong-jun[a], ZHU Shao-lan[a], HU Shao-lei[a], ZHAO Hui[a,b], MA Zhen[a,b], CHEN Rong-li[a,b], QIU Yue-hong[a,b], GAO Wei[a,b], FAN Xue-wu[a,b], ZHAO Bao-chang[a,b], LI Ying-cai[a,b]

(a. *Joint Research Laboratory of High Resolution Optical Imaging*, *State Key Laboratory of Transient Optics and Photonics*; b. *Laboratory of Space Optical Technology*, *Xi'an Institute Optics and Precision Mechanics*, *Chinese Academy of Sciences*, *Xi'an* 710119, *China*)

Abstract: A new kind of space-based telescope with variable resolution at any field angle by active optical zoom is proposed theoretically. It can change the magnification of imaging system at any field angle that means the effective focal length can be changed at a limited region of interest and simultaneously maintain high resolution. It comprises two static aspheric mirrors and two deformable mirrors and the focal length can be adjusted from 399 to 558.6 mm by changing the curvature of the two deformable mirrors. Comparing with the mechanical zoom systems, they are active optical zoom systems, in addition, they avoid the precisely moving of elements and reduce the response time. The imaging quality of this optical zoom system is examined by analyzing the Spot Diagrams and the Modulation Transfer Function (MTF) curves at different field of view especially about the outside of the specific FOV. The Root Mean Square (RMS) radius of field angle at 0, 0.51 and 0.7 degrees are about 1.6 μm, 1.0 μm, and 1.7 μm, respectively, and the MTF values in the Spatial Frequency (SF) of 68 lp/mm is almost unchanged at 0.7. The novel system reduces the bandwidth of data transmission and may find potential applications in remote sensing.

Key words: Any field angle; Deformable mirror; Active zoom system; Optical systems design

CLCN:V474.2+7 **Document Code**:A **doi**:10.3788/gzxb20114011.1619

0 Introduction

Because of the extensive application in civilian and military fields, the optical zoom systems have been intensively investigated in the past tens of years[1-5]. The conventional zoom systems are usually obtained using mechanical method, which change the focal length of system by adjusting the separations between individual or groups of optical elements, such as lenses, mirrors[6-7]. Recently, the optical zoom systems without moving elements have been proposed[8-10]. S. Kuiper *et al*. have designed a zoom camera which is based on two-focus liquid lenses and three plastic lenses[8]. K. Seidl *et al*. have developed an all-reflective unobscured optical-power zoom objective with two Deformable Mirrors (DMs) and two static aspheric mirrors[9]. Especially, Yang Lu *et al*. have described a polymorphic optical zoom system with two deformable mirrors, moreover, it is experimentally proved that such a system is capable of automated fine focus control and adaptive aberration compensation[10]. These systems can successfully change the magnification of an imaging system by using of liquid lenses or deformable mirrors[11-13]. Compare with the mechanical zoom systems, they are active optical zoom systems, in addition, they avoid the precisely moving of elements and reduce the response time[14-15].

However, these optical zoom systems still have certain limitations. The Field Of View (FOV) is inverse proportional to the zoom ratio. Namely, if there is a system with a FOV of 1.8 degrees and a 1.5∶1 zoom ration is desired, then a FOV of 1.2 degrees after zoom would be needed.

Foundation item:The National Nature Science Foundation of China (No. 60878034) and the National High Technology Research and Development Program of China

First author:XIE Yong-jun(1974—), male, associate researcher, mainly focuses on diffractive optics and remote sensing.
Email:yjxie@opt.ac.cn

Received date:2011-10-22 **Revised date**:2011-11-18

As a result, the active optical zoom systems can only transmit the information of the image in the specific FOV (for the given example, it is inside the 1.2 degrees) and the information of the other region (outside of the specific FOV) is lost. Additionally, both the conventional and active optical zoom systems need complex devices for the data transmission, especially for the space-based optical zoom system. So that arises a severe problem: how to transmit the information of the outside of the specific FOV and simplify the system structure?

In our former papers, we have already experimentally demonstrated that the geometrical aberrations of any field of view can be corrected by adjusting a deformable mirror[16-17]. Based on this fact, we have theoretically proposed a new kind of active optical zoom system in this paper. Similar with the mentioned zoom systems in[10], we also employ two deformable mirrors for changing the effective focal length, but our system possesses a wide FOV and can realize zoom at any field of angle, especially outside of the specific FOV. Namely, our system can change the effective focal length at a limited region of interest. So it can reduce the data transmission bandwidth of a system and simultaneously maintain high resolution over a limited area of interest. The proposed active optical zoom system consists of four mirrors, which has a zoom ratio of 1.4 : 1 (from −399 to −558.6 mm). Its entrance pupil diameter is 80 mm, the $F/\#$ range is from 5.0 to 7.0 and the FOV is 1.44 degrees. The proposed active optical zoom system profits from compact as well as low power consumption features, and paves a new way to realize the imaging of the outside of the specific FOV.

1 The principle of imaging in zoom system

Consider a coaxial reflective zoom system with four mirrors as shown in Fig. 1.

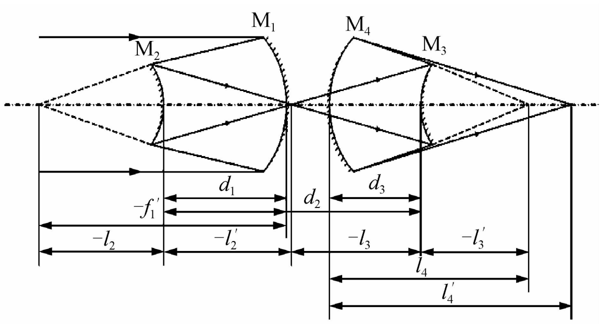


Fig. 1 A coaxial reflective zoom system with four mirrors

The M_1, M_2, M_3, M_4 correspond to the four mirrors as shown in Fig. 1, d_1, d_2, d_3, are the distances between the four mirrors, l_1, l_2, l_3, l_4 are the distances of object, and $l_1=\infty$, $f_1'=\frac{1}{2}r_1$.

According to the Gaussian formula, we can obtain equations as following

$$\frac{1}{l_2'}-\frac{1}{l_2}=\frac{1}{f_2}=\frac{2}{r_2}\qquad (1)$$
$$-l_2=-f_1'+d_1$$

$$\frac{1}{l_3'}-\frac{1}{l_3}=\frac{1}{f_3'}=\frac{2}{r_3}\qquad (2)$$
$$-l_3=l_2'-d_2$$

$$\frac{1}{l_4'}+\frac{1}{l_4}=\frac{1}{f_4'}=\frac{2}{r_4}\qquad (3)$$
$$l_4=l_3'+d_3$$

So the l_2', l_3', l_4' can be written in the form as following

$$l_2'=\frac{\frac{1}{2}r_1r_2-d_1r_2}{r_1-2d_1+r_2}$$
$$l_3'=\frac{r_3d_2-r_3l_2'}{2d_2-2l_2'+r_3}\qquad (4)$$
$$l_4'=\frac{r_4d_3+r_4l_3'}{2d_3+2l_3'-r_4}$$

And then the magnifications of the mirrors β_2, β_3, β_4 are obtained

$$\beta_2=-\frac{l_2'}{l_2}=-\frac{r_2}{r_1-2d_1+r_2}$$
$$\beta_3=-\frac{r_3}{2d_2-2l_2'+r\beta}\qquad (5)$$
$$\beta_4=-\frac{r_4}{2d_3+2l_3'-r_4}$$

So the total focal length f' of the whole reflective zoom system can be expressed as

$$f'=f_1'\beta_2\beta_3\beta_4=-\frac{1}{2}r_1\times\frac{r_2}{r_1-2d_1+r_2}\times\frac{r_3}{2d_2-2l_2'+r_3}\times\frac{r_4}{2d_3+2l_3'-r_4}\qquad (6)$$

The effective focal length of the zoom system can be varied by changing any curvature of the mirrors, but we need maintain the place image plane, so we employ two deformable mirrors to adjust the focal length without changing image plane.

2 Active optical system for any field angle zoom

In active optical zoom system, two variable groups are the key devices for adjustable focal length and fixed image plane. The variable groups could be liquid lenses or deformable mirrors.

The liquid lens works base on the principle of electrowetting which controls the wetting properties of a liquid on a solid by modifying the applied voltage at the solid-liquid interface[18-19].

The optical zoom system with liquid lenses has advantages of high speed zoom, large range of optical zoom, light weight and low power consumption[20-21]. However, due to the limited number of available materials known to possess a suitable combination of properties such as refractive index, Abbe number, transparency, and viscosity, there are a lot of difficulty to realize an optical zoom system which reaches adequate imaging quality. Especially, it is quite difficult to correct the chromatic aberrations for the proposed system[22].

With the using of an array of actuators which can change the shape of a mirror, the curvature of the deformable mirror can alter in a certain range just as the liquid lens zoom system does. Compare to the liquid lenses optical zoom system, the deformable mirror zoom system has a distinct advantage of being free of chromatic aberrations[23-25]. So we employ two deformable mirrors to be variable elements to realize optical zoom in our system. The principle part of the system consists of a Cassegrain and a Cassegrain-inverse configuration. The layout of the active optical zoom system used in our simulation is shown schematically in Fig. 2.

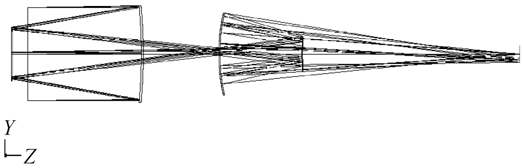


Fig. 2　Layout of the active optical system for any field angle zoom

There are totally four mirrors in the proposed system as shown in Fig. 2. The primary and quaternary mirrors are static aspheric mirrors, however, the secondary and the tertiary mirror are deformable mirrors. The design parameters of the zoom system are listed in Table 1.

Table 1　Design parameters of the zoom system

Surface	Primary	Secondary DM_1	Tertiary DM_2	Quaternary	Focal length/mm
Radius/mm	−464.695	−891.166	204.068	159.140	−399
		−715.684	311.094		−558.6
		−715.636	311.740		
		−715.586	312.416		
Separation/mm	110.396	248.160	70.358	256.886	
Conic	−0.456	0	−6.569	−0.105	

The effective focal length of the system can be adjusted from −399 to −558.6 mm by changing the curvature of the two deformable mirrors as shown in Table 1. Today, many companies have the ability to produce deformable mirrors, such as OKO Technologies, Iris AO Inc, and Boston Micromachines corporation. However, the deflection of these deformable mirrors is relatively small (~2 diopters) Recently, J. Wang *et al* have fabricated an organic polymer deformable mirror which can be operated over a large optical power range of up to 20 diopters[26]. The optical power range of deformable mirrors in our system are designed to be −2.44~2.79(−891.166~715.586) and 9.8~6.4 diopters (204.068~312.416), respectively. So from the point view of engineering applications, it is possible to employ the deformable mirrors in the system design.

We examine the imaging quality of this optical zoom system by analyzing the Spot Diagrams and the Modulation Transfer Function (MTF) curves at different field of view especially about the outside of the specific FOV. Fig. 3. gives the Spot Diagrams and the MTF curves of different FOV in

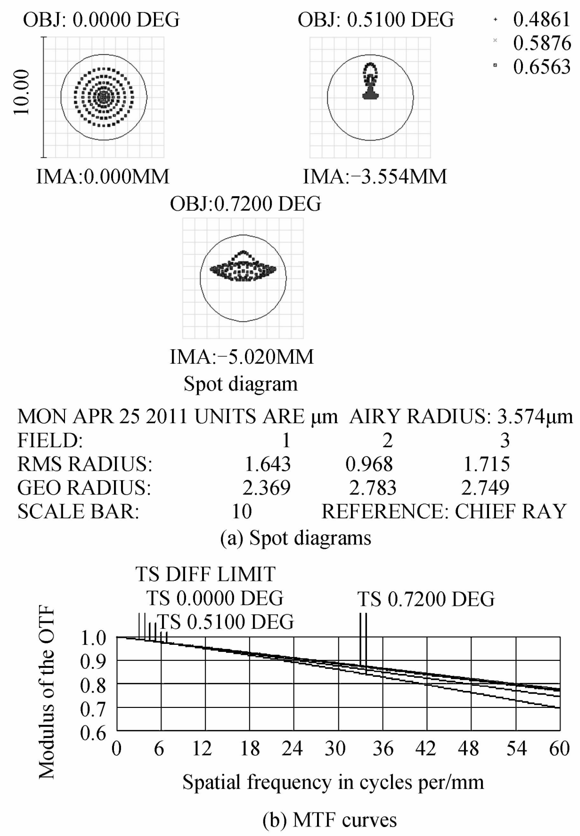


Fig. 3　Spot diagrams and MTF curves for the unzoomed system at $f=-399$ mm

the unzoomed system at $f=-399$ mm. Fig. 3 shows that the different FOV perform similar imaging quality in the unzoomed system. The Root Mean Square (RMS) radius of field angle at 0, 0.51 and 0.7 degrees are about 1.6 μm, 1.0 μm, and 1.7 μm, respectively, and the MTF values in the Spatial Frequency (SF) of 68 lp/mm is almost unchanged at 0.7.

But in the zoomed system, the situation would be quit different. Fig. 4～6 demonstrate the system characters when the curvatures of the two deformable mirrors respectively are −715.684/311.094 mm, −715.636/311.740 mm, and −715.586/312.419 mm.

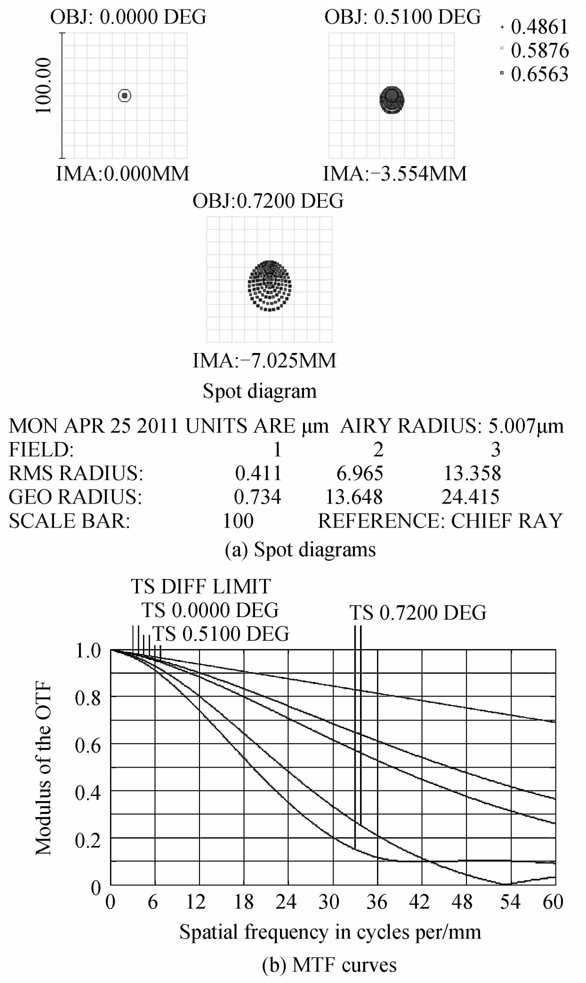


Fig. 4 Spot diagrams and MTF curves for $f=-558.6$ mm, $r_2=-715.684$ mm, $r_3=311.094$ mm

Fig. 4 shows that the RMS radius is ～0.41 μm and the MTF values in the SF of 68 lp/mm is ～0.70 in the situation of 0 degree FOV. But corresponding with the field angle of 0.51 and 0.72 degrees, the RMS radius (MTF values) is ～6.97 μm and 13.4 μm (～0.3 and ～0.1). It is obvious that the imaging quality about the specified FOV is quit well whereas it is awful for that of the other FOV.

However, Fig. 5 shows the RMS radius is about ～2.0 μm and the MTF values in the SF of 68 lp/mm is ～0.68 in the situation of 0.51 degree. But corresponding with the field of angles of 0 and 0.72 degrees, the RMS radius (MTF values) is ～6.1 μm and 7.3 μm (～0.3 and ～0.4). It is obvious that the imaging quality about an edge of the specific FOV is quite well.

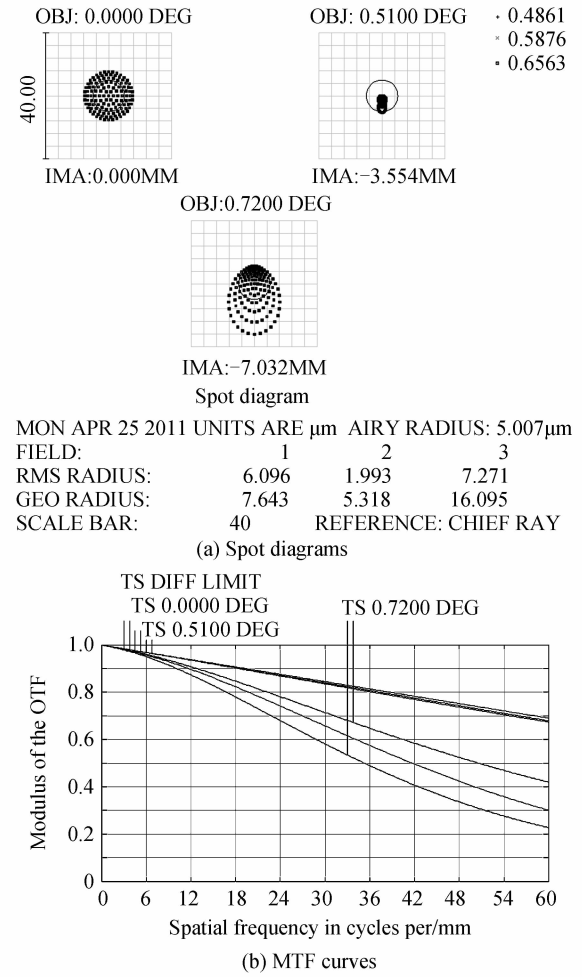
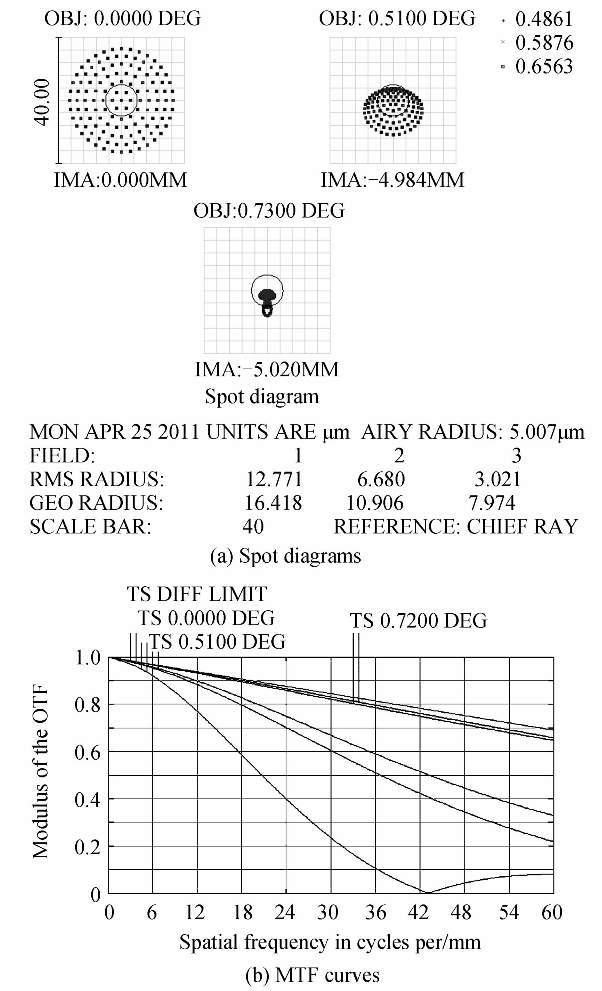


Fig. 5 Spot diagrams and MTF curves for $f=-558.6$ mm, $r_2=-715.636$ mm, $r_3=311.740$ mm

In addition, in Fig. 6, the RMS radius is ～3.0 μm, the MTF values in the SF of 68 lp/mm almost is ～0.65 in the situation of 0.72 degrees the outside of the specific FOV. But corresponding with the other field angle at 0 and 0.51 degrees, the RMS radius (MTF values) is ～6.7 μm and 12.8 μm (～0.1 and ～0.3). It is obvious that the imaging quality about the outside of the specific FOV is quite well. Furthermore, accordingly to Fig. 6, this system has a wide FOV (the whole FOV is 1.44 degrees) when it has finished optical zoom, while the whole FOV of other zoom systems is relatively small (the whole FOV is 1.02 degrees). Fig. 7 present the remote sensing simulation of this telescope.



(a) Spot diagrams

(b) MTF curves

Fig. 6　Spot diagrams and MTF curves for $f=-558.6$ mm, $r_2=-715.586$ mm, $r_3=312.419$ mm

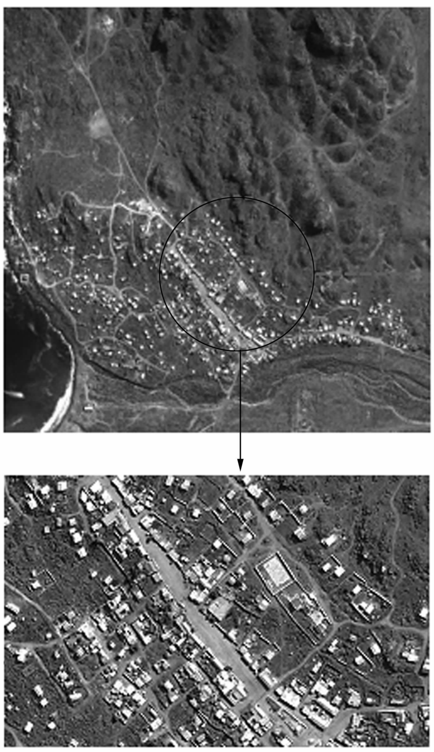


Fig. 7　The selected field with higher resolution can be achieved by optical zoom

Accordingly to above discussion, these results successfully demonstrate this active optical zoom system has a wide FOV and can vary the effective focal length of the system at the different angle field of view. Especially, it can change the effective focal length at the outside of the specific FOV. And the zoomed imaging quality approaches the diffraction-limited at these field angles.

3　Conclusion

In this paper, we have proposed a new kind of active optical zoom system which exhibits a good imaging quality. In addition, the system parameters are analyzed, which demonstrates the new active optical zoom system is practical and feasible. And the simulation shows that effective focal length can change at any field angle. Besides, the imaging quality in these field angles approaches diffraction-limited. So the zoom system may pave a new way to reduce the bandwidth of data transmission.

References

[1]　BETENSKY E. Zoom lens for small CCD camera[C]. *SPIE*, 1995, **2539**: 2-11.

[2]　MIKS A, NOVAK J, NOVAK P. Method of zoom lens design [J]. *Applied Optics*, 2008, **47**(32): 6088-6098.

[3]　SANSON M C, CORNELL J. MWIR continuous zoom with large zoom range[C]. *SPIE*, 2010, **7660**: 76601X.

[4]　JOHNSON R B, HADAWAY J B, BURLESON T. All-reflective four-element zoom telescope: design and analysis [C]. *SPIE*, 1990, **1354**: 669-675.

[5]　ZHANG T, WANG Y, CHAN J. Design of unobscured reflective zoom system with three mirrors[J]. *Chinese Optics Letters*, 2010, **8**(7): 701-705.

[6]　CHANG J, WANG Y, ZHANG T, *et al*. All reflective zoom systems for infrared optics[C]. *SPIE*, 2006, **6342**: 6342Q.

[7]　OLSON C, GOODMAN T, ADDIEGO C, *et al*. Design and construction of a short-wave infrared 3.3X continuous zoom lens[C]. *SPIE*, 2010, **7652**: 76522A.

[8]　KUIPER S, HENDRIKS B H W, SUIJVER J F, *et al*. Zoom camera based on liquid lenses [C]. *SPIE*, 2007, **6466**: 64660F.

[9]　SEIDL K, KNOBBE J, GRÜGER H. Design of an all-reflective unobscured optical-power zoom objective [J]. *Applied Optics*, 2009, **48**(21): 4097-4107.

[10]　LU Y, HOFFMAN S M, STOCKBRIDGE C R, *et al*. Polymorphic optical zoom with MEMS DMs [C]. *SPIE*, 2011, **7931**: 79310D.

[11]　MIKS A, NOVAK J. Analysis of two-element zoom system based on variable power lenses[J]. *Optics Express*, 2010, **18**(7): 6797-6810.

[12]　KUIPER S, HENDRIKS B H W. Variable-focus liquid lens for miniature cameras[J]. *Applied Physics Letters*, 2004, **85**(7): 1128-1138.

[13]　WICK V, BAGWELL B E, SWEATT W C, *et al*. Active optical zoom for space-based imaging [C]. *SPIE*, 2006, **6307**: 63070A.

[14]　SAUREI L, MATHIEU G, BERGE B. Design of an

autofocus lens for VGA 1/4″ CCD and CMOS sensors[C]. *SPIE*, 2004, **5249**: 288-296.

[15] WICK V, MARTINEZ T, PAYNE D M, *et al*. Active optical zoom system[C]. *SPIE*, 2005, **5798**: 151-157.

[16] ZHAO X, XIE Y, ZHAO W. Broadband and wide field of view foveated imaging system in space [J]. *Optical Engineering*, 2008, **47**(10): 1-1-1-5.

[17] ZHAO X, XIE Y, ZHAO W. Wide field-of-view foveated imaging system[J]. *Chinese Optics Letters*, 2008, **6**(8): 561-563.

[18] BERGA B, PESEUX J. Variable focal lens controlled by an external voltage: an application of electrowetting[J]. *The European Physical Journal E*, 2000, **3**(2): 159-163.

[19] PENG R, CHEN J, CHENG C, *et al*. Design of a zoom lens without motorized optical elements[J]. *Optics Express*, 2007, **15**(11): 6664-6669.

[20] VALLEY P, DODGE M R, SCHWIEGERLING J, *et al*. Non mechanical bifocal zoom telescope[J]. *Optics Letters*, 2010, **35**(15): 2582-2584.

[21] REN H, WU S. Variable-focus liquid lens[J]. *Optics Express*, 2007, **15**(10): 5931-5936.

[22] REICHELT S, ZAPPE H. Design of spherically corrected, achromatic variable-focus liquid lenses[J]. *Optics Express*, 2007, **15**(21): 14146-14154.

[23] ZHU L, SUN P, FAINMAN Y. Aberration-free dynamic focusing with a multichannel micromachined membrane deformable mirror[J]. *Applied Optics*, 1999, **38**(25): 5350-5354.

[24] ZHU L, SUN P, BARTSCH D, *et al*. Adaptive control of a micromachined continuous-membrane deformable for aberration compensation[J]. *Applied Optics*, 1999, **38**(1): 168-167.

[25] PATERSON C, MUNRO I, DAINTY J C. A low cost adaptive optics system using a membrane mirror[J]. *Optics Express*, 2000, **6**(9): 175-185.

[26] WANG J, CHEN T, LIU C, *et al*. Polymer deformable mirror for optical auto focusing[J]. *ETRI Journal*, 2007, **29**(6): 817-819.

基于主动光学技术的任意视场变分辨率空间望远镜

谢永军[a],朱少岚[a],胡少磊[a],赵惠[a,b],马臻[a,b],陈荣利[a,b],邱跃洪[a,b],高伟[a,b],樊学武[a,b],赵葆常[a,b],李英才[a,b]

(中国科学院西安光学精密机械研究所 a.瞬态光学与光子技术国家重点实验室 高分辨光学成像技术联合实验室;
b.空间光学技术实验室,西安 710119)

摘　要:介绍了一种新型的空间望远镜,通过改变光学系统焦距,可以提高任意感兴趣视场的成像分辨率。光学系统有四个反射镜组成,包括两个静态非球面反射镜和两个面形动态可调非球面反射镜.通过改变两个可变形反射镜的面形,系统焦距可以在 399 mm 到 558 mm 范围内进行动态调整.和机械式变焦系统相比,此主动变焦系统避免了光学元件的精密移动,有效减少反应时间。分析了此系统的成像质量,给出了 0°、0.51°、0.7°不同视场的弥散斑:1.6 μm、1.0 μm、1.7 μm,及传递函数:在 68 lp/mm 时,MTF 曲线值大于 0.7.此新型成像技术还可以有效减少数据传输链带宽需求,在遥感领域具有广阔的应用前景.

关键词:主动变焦系统;光学系统设计;可变形镜;任意视场角