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(54) **HIGH RESOLUTION THIN MULTI-APERTURE IMAGING SYSTEMS**

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(56) **References Cited**

U.S. PATENT DOCUMENTS

4,199,785 A 4/1980 McCullough et al.
5,005,083 A 4/1991 Grage et al.
(Continued)

FOREIGN PATENT DOCUMENTS

CN 101276415 A 10/2008
CN 201514511 U 6/2010
(Continued)

OTHER PUBLICATIONS

Statistical Modeling and Performance Characterization of a Real-Time Dual Camera Surveillance System, Greienhagen et al., Publisher: IEEE, 2000, 8 pages.

(Continued)

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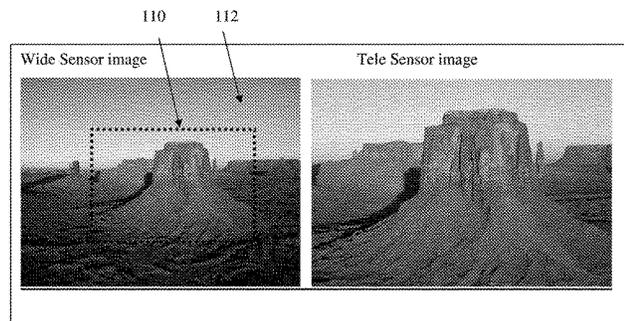
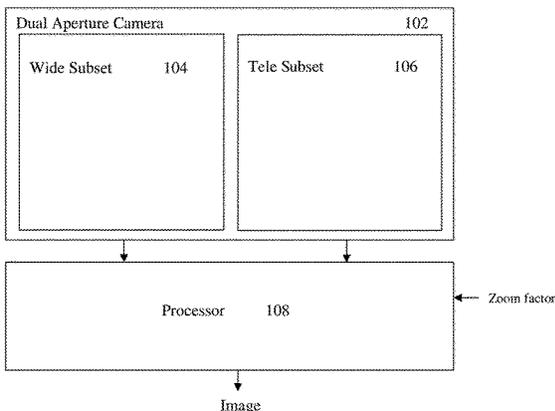
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(57) **ABSTRACT**

A multi-aperture imaging system comprising a first camera with a first sensor that captures a first image and a second camera with a second sensor that captures a second image, the two cameras having either identical or different FOVs. The first sensor may have a standard color filter array (CFA) covering one sensor section and a non-standard color CFA covering another. The second sensor may have either Clear or standard CFA covered sections. Either image may be chosen to be a primary or an auxiliary image, based on a zoom factor. An output image with a point of view determined by the primary image is obtained by registering the auxiliary image to the primary image.

5 Claims, 7 Drawing Sheets

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See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

- 5,032,917 A 7/1991 Aschwanden
- 5,041,852 A 8/1991 Misawa et al.
- 5,051,830 A 9/1991 von Hoessle
- 5,099,263 A 3/1992 Matsumoto et al.
- 5,248,971 A 9/1993 Mandl
- 5,287,093 A 2/1994 Amano et al.
- 5,394,520 A 2/1995 Hall
- 5,436,660 A 7/1995 Sakamoto
- 5,444,478 A 8/1995 Lelong et al.
- 5,459,520 A 10/1995 Sasaki
- 5,657,402 A 8/1997 Bender et al.

- 5,682,198 A 10/1997 Katayama et al.
- 5,768,443 A 6/1998 Michael et al.
- 5,926,190 A 7/1999 Turkowski et al.
- 5,940,641 A 8/1999 McIntyre et al.
- 5,982,951 A 11/1999 Katayama et al.
- 6,101,334 A 8/2000 Fantone
- 6,128,416 A 10/2000 Oura
- 6,148,120 A 11/2000 Sussman
- 6,208,765 B1 3/2001 Bergen
- 6,268,611 B1 7/2001 Pettersson et al.
- 6,549,215 B2 4/2003 Jouppi
- 6,611,289 B1 8/2003 Yu et al.
- 6,643,416 B1 11/2003 Daniels et al.
- 6,650,368 B1 11/2003 Doron
- 6,680,748 B1 1/2004 Monti
- 6,714,665 B1 3/2004 Hanna et al.
- 6,724,421 B1 4/2004 Glatt
- 6,738,073 B2 5/2004 Park et al.
- 6,741,250 B1 5/2004 Furlan et al.
- 6,750,903 B1 6/2004 Miyatake et al.
- 6,778,207 B1 8/2004 Lee et al.
- 7,002,583 B2 2/2006 Rabb, III
- 7,015,954 B1 3/2006 Foote et al.
- 7,038,716 B2 5/2006 Klein et al.
- 7,199,348 B2 4/2007 Olsen et al.
- 7,206,136 B2 4/2007 Labaziewicz et al.
- 7,248,294 B2 7/2007 Slatter
- 7,256,944 B2 8/2007 Labaziewicz et al.
- 7,305,180 B2 12/2007 Labaziewicz et al.
- 7,339,621 B2 3/2008 Fortier
- 7,346,217 B1 3/2008 Gold, Jr.
- 7,365,793 B2 4/2008 Cheatle et al.
- 7,411,610 B2 8/2008 Doyle
- 7,424,218 B2 9/2008 Baudisch et al.
- 7,509,041 B2 3/2009 Hosono
- 7,533,819 B2 5/2009 Barkan et al.
- 7,561,191 B2 7/2009 May et al.
- 7,619,683 B2 11/2009 Davis
- 7,676,146 B2 3/2010 Border et al.
- 7,738,016 B2 6/2010 Toyofuku
- 7,773,121 B1 8/2010 Huntsberger et al.
- 7,809,256 B2 10/2010 Kuroda et al.
- 7,880,776 B2 2/2011 LeGall et al.
- 7,918,398 B2 4/2011 Li et al.
- 7,964,835 B2 6/2011 Olsen et al.
- 7,978,239 B2 7/2011 Deever et al.
- 8,094,208 B2* 1/2012 Myhrvold H04N 5/2254 348/222.1
- 8,115,825 B2 2/2012 Culbert et al.
- 8,134,115 B2 3/2012 Koskinen et al.
- 8,149,327 B2 4/2012 Lin et al.
- 8,154,610 B2 4/2012 Jo et al.
- 8,179,457 B2 5/2012 Koskinen et al.
- 8,238,695 B1 8/2012 Davey et al.
- 8,274,552 B2 9/2012 Dahi et al.
- 8,390,729 B2 3/2013 Long et al.
- 8,391,697 B2 3/2013 Cho et al.
- 8,400,555 B1 3/2013 Georgiev et al.
- 8,439,265 B2 5/2013 Ferren et al.
- 8,446,484 B2 5/2013 Muukki et al.
- 8,483,452 B2 7/2013 Ueda et al.
- 8,514,491 B2 8/2013 Duparre
- 8,542,287 B2 9/2013 Griffith et al.
- 8,547,389 B2 10/2013 Hoppe et al.
- 8,553,106 B2 10/2013 Scarff
- 8,587,691 B2 11/2013 Takane
- 8,619,148 B1 12/2013 Watts et al.
- 8,660,420 B2 2/2014 Chang
- 8,803,990 B2 8/2014 Smith
- 8,896,655 B2 11/2014 Mauchly et al.
- 8,976,255 B2 3/2015 Matsuoto et al.
- 9,019,387 B2 4/2015 Nakano
- 9,025,073 B2 5/2015 Attar et al.
- 9,025,077 B2 5/2015 Attar et al.
- 9,041,835 B2 5/2015 Honda
- 9,137,447 B2 9/2015 Shibuno
- 9,185,291 B1 11/2015 Shabtay et al.
- 9,215,377 B2 12/2015 Sokeila et al.
- 9,215,385 B2 12/2015 Luo

(56)

References Cited

U.S. PATENT DOCUMENTS

9,270,875	B2	2/2016	Brisedoux et al.	2008/0218612	A1	9/2008	Border et al.	
9,286,680	B1	3/2016	Jiang et al.	2008/0218613	A1	9/2008	Janson et al.	
9,344,626	B2	5/2016	Silverstein et al.	2008/0219654	A1	9/2008	Border et al.	
9,360,671	B1	6/2016	Zhou	2009/0086074	A1	4/2009	Li et al.	
9,369,621	B2	6/2016	Malone et al.	2009/0109556	A1	4/2009	Shimizu et al.	
9,413,930	B2	8/2016	Geerds	2009/0122195	A1	5/2009	Van Baar et al.	
9,413,984	B2	8/2016	Attar et al.	2009/0122406	A1	5/2009	Rouvinen et al.	
9,420,180	B2	8/2016	Jin	2009/0128644	A1	5/2009	Camp et al.	
9,438,792	B2	9/2016	Nakada et al.	2009/0219547	A1	9/2009	Kauhanen et al.	
9,485,432	B1	11/2016	Medasani et al.	2009/0252484	A1	10/2009	Hasuda et al.	
9,578,257	B2	2/2017	Attar et al.	2009/0295949	A1	12/2009	Ojala	
9,618,748	B2	4/2017	Munger et al.	2009/0324135	A1	12/2009	Kondo et al.	
9,681,057	B2	6/2017	Attar et al.	2010/0013906	A1	1/2010	Border et al.	
9,723,220	B2	8/2017	Sugie	2010/0020221	A1	1/2010	Tupman et al.	
9,736,365	B2	8/2017	Laroia	2010/0060746	A9	3/2010	Olsen et al.	
9,736,391	B2	8/2017	Du et al.	2010/0097444	A1	4/2010	Lablans	
9,768,310	B2	9/2017	Ahn et al.	2010/0103194	A1	4/2010	Chen et al.	
9,800,798	B2	10/2017	Ravirala et al.	2010/0165131	A1	7/2010	Makimoto et al.	
9,851,803	B2	12/2017	Fisher et al.	2010/0196001	A1	8/2010	Ryynänen et al.	
9,894,287	B2	2/2018	Qian et al.	2010/0238327	A1	9/2010	Griffith et al.	
9,900,522	B2	2/2018	Lu	2010/0259836	A1	10/2010	Kang et al.	
9,927,600	B2	3/2018	Goldenberg et al.	2010/0277619	A1	11/2010	Scarff	
2002/0005902	A1	1/2002	Yuen	2010/0283842	A1	11/2010	Guissin et al.	
2002/0030163	A1	3/2002	Zhang	2010/0321494	A1	12/2010	Peterson et al.	
2002/0063711	A1	5/2002	Park et al.	2011/0058320	A1	3/2011	Kim et al.	
2002/0075258	A1	6/2002	Park et al.	2011/0063417	A1	3/2011	Peters et al.	
2002/0122113	A1	9/2002	Foote	2011/0063446	A1	3/2011	McMordie et al.	
2002/0167741	A1	11/2002	Koiwai et al.	2011/0064327	A1*	3/2011	Dagher	G06T 5/004 382/263
2003/0030729	A1	2/2003	Prentice et al.	2011/0080487	A1	4/2011	Venkataraman et al.	
2003/0093805	A1	5/2003	Gin	2011/0121421	A1	5/2011	Charbon et al.	
2003/0160886	A1	8/2003	Misawa et al.	2011/0128288	A1	6/2011	Petrou et al.	
2003/0202113	A1	10/2003	Yoshikawa	2011/0164172	A1	7/2011	Shintani et al.	
2004/0008773	A1	1/2004	Itokawa	2011/0216228	A1*	9/2011	Kawamura	H04N 5/335 348/273
2004/0012683	A1	1/2004	Yamasaki et al.	2011/0229054	A1	9/2011	Weston et al.	
2004/0017386	A1	1/2004	Liu et al.	2011/0234798	A1	9/2011	Chou	
2004/0027367	A1	2/2004	Pilu	2011/0234853	A1	9/2011	Hayashi et al.	
2004/0061788	A1	4/2004	Bateman	2011/0234881	A1	9/2011	Wakabayashi et al.	
2004/0141065	A1	7/2004	Hara et al.	2011/0242286	A1	10/2011	Pace et al.	
2004/0141086	A1	7/2004	Mihara	2011/0242355	A1	10/2011	Goma et al.	
2004/0240052	A1	12/2004	Minefuji et al.	2011/0285730	A1	11/2011	Lai et al.	
2005/0013509	A1	1/2005	Samadani	2011/0292258	A1	12/2011	Adler et al.	
2005/0046740	A1	3/2005	Davis	2011/0298966	A1	12/2011	Kirschstein et al.	
2005/0157184	A1	7/2005	Nakanishi et al.	2012/0026366	A1	2/2012	Golan et al.	
2005/0168834	A1	8/2005	Matsumoto et al.	2012/0044372	A1	2/2012	Cote et al.	
2005/0185049	A1	8/2005	Iwai et al.	2012/0062780	A1	3/2012	Morihisa	
2005/0200718	A1	9/2005	Lee	2012/0069235	A1	3/2012	Imai	
2006/0054782	A1	3/2006	Olsen et al.	2012/0075489	A1	3/2012	Nishihara	
2006/0056056	A1	3/2006	Ahiska et al.	2012/0081566	A1*	4/2012	Cote	H04N 5/2256 348/222.1
2006/0067672	A1	3/2006	Washisu et al.	2012/0105579	A1	5/2012	Jeon et al.	
2006/0102907	A1	5/2006	Lee et al.	2012/0124525	A1	5/2012	Kang	
2006/0125937	A1	6/2006	LeGall et al.	2012/0154547	A1	6/2012	Aizawa	
2006/0170793	A1	8/2006	Pasqualette et al.	2012/0154614	A1	6/2012	Moriya et al.	
2006/0175549	A1	8/2006	Miller et al.	2012/0196648	A1	8/2012	Havens et al.	
2006/0187310	A1	8/2006	Janson et al.	2012/0229663	A1	9/2012	Nelson et al.	
2006/0187322	A1	8/2006	Janson et al.	2012/0249815	A1	10/2012	Bohn et al.	
2006/0187338	A1	8/2006	May et al.	2012/0287315	A1	11/2012	Huang et al.	
2006/0227236	A1	10/2006	Pak	2012/0320467	A1	12/2012	Baik et al.	
2007/0024737	A1	2/2007	Nakamura et al.	2013/0002928	A1	1/2013	Imai	
2007/0126911	A1	6/2007	Nanjo	2013/0016427	A1	1/2013	Sugawara	
2007/0127040	A1	6/2007	Davidovici	2013/0063629	A1	3/2013	Webster et al.	
2007/0177025	A1	8/2007	Kopet et al.	2013/0076922	A1	3/2013	Shihoh et al.	
2007/0188653	A1	8/2007	Pollock et al.	2013/0093842	A1	4/2013	Yahata	
2007/0189386	A1	8/2007	Imagawa et al.	2013/0094126	A1	4/2013	Rappoport et al.	
2007/0257184	A1	11/2007	Olsen et al.	2013/0113894	A1	5/2013	Mirlay	
2007/0285550	A1	12/2007	Son	2013/0135445	A1	5/2013	Dahi et al.	
2008/0017557	A1	1/2008	Witdouck	2013/0136355	A1*	5/2013	Demandolx	H04N 5/3572 382/167
2008/0024614	A1	1/2008	Li et al.	2013/0155176	A1	6/2013	Paripally et al.	
2008/0025634	A1	1/2008	Border et al.	2013/0182150	A1	7/2013	Asakura	
2008/0030592	A1	2/2008	Border et al.	2013/0201360	A1	8/2013	Song	
2008/0030611	A1	2/2008	Jenkins	2013/0202273	A1	8/2013	Ouedraogo et al.	
2008/0084484	A1	4/2008	Ochi et al.	2013/0235224	A1	9/2013	Park et al.	
2008/0106629	A1	5/2008	Kurtz et al.	2013/0250150	A1	9/2013	Malone et al.	
2008/0117316	A1	5/2008	Orimoto	2013/0258044	A1	10/2013	Betts-LaCroix	
2008/0129831	A1	6/2008	Cho et al.	2013/0270419	A1	10/2013	Singh et al.	
2008/0218611	A1	9/2008	Parulski et al.	2013/0278785	A1	10/2013	Nomura et al.	

(56)

References Cited

U.S. PATENT DOCUMENTS

2013/0321668 A1 12/2013 Kamath
 2014/0009631 A1 1/2014 Topliss
 2014/0049615 A1 2/2014 Uwagawa
 2014/0118584 A1 5/2014 Lee et al.
 2014/0192238 A1 7/2014 Attar et al.
 2014/0192253 A1 7/2014 Laroia
 2014/0218587 A1 8/2014 Shah
 2014/0313316 A1 10/2014 Olsson et al.
 2014/0362242 A1 12/2014 Takizawa
 2015/0002683 A1 1/2015 Hu et al.
 2015/0042870 A1 2/2015 Chan et al.
 2015/0070781 A1 3/2015 Cheng et al.
 2015/0092066 A1 4/2015 Geiss et al.
 2015/0103147 A1 4/2015 Ho et al.
 2015/0138381 A1 5/2015 Ahn
 2015/0154776 A1 6/2015 Zhang et al.
 2015/0162048 A1 6/2015 Hirata et al.
 2015/0195458 A1 7/2015 Nakayama et al.
 2015/0215516 A1 7/2015 Dolgin
 2015/0237280 A1 8/2015 Choi et al.
 2015/0242994 A1 8/2015 Shen
 2015/0244906 A1 8/2015 Wu et al.
 2015/0253543 A1 9/2015 Mercado
 2015/0253647 A1 9/2015 Mercado
 2015/0261299 A1 9/2015 Wajs
 2015/0271471 A1 9/2015 Hsieh et al.
 2015/0281678 A1 10/2015 Park et al.
 2015/0286033 A1 10/2015 Osborne
 2015/0316744 A1 11/2015 Chen
 2015/0334309 A1 11/2015 Peng et al.
 2016/0044250 A1 2/2016 Shabtay et al.
 2016/0070088 A1 3/2016 Koguchi
 2016/0154202 A1 6/2016 Wippermann et al.
 2016/0154204 A1 6/2016 Lim et al.
 2016/0212358 A1 7/2016 Shikata
 2016/0212418 A1 7/2016 Demirdjian et al.
 2016/0241751 A1 8/2016 Park
 2016/0291295 A1 10/2016 Shabtay et al.
 2016/0295112 A1 10/2016 Georgiev et al.
 2016/0301840 A1 10/2016 Du et al.
 2016/0353008 A1 12/2016 Osborne
 2016/0353012 A1 12/2016 Kao et al.
 2017/0019616 A1 1/2017 Zhu et al.
 2017/0070731 A1 3/2017 Darling et al.
 2017/0187962 A1 6/2017 Lee et al.
 2017/0214846 A1 7/2017 Du et al.
 2017/0214866 A1 7/2017 Zhu et al.
 2017/0242225 A1 8/2017 Fiske
 2017/0289458 A1 10/2017 Song et al.
 2018/0013944 A1 1/2018 Evans, V et al.
 2018/0017844 A1 1/2018 Yu et al.
 2018/0024329 A1 1/2018 Goldenberg et al.
 2018/0059379 A1 3/2018 Chou
 2018/0120674 A1 5/2018 Avivi et al.
 2018/0150973 A1 5/2018 Tang et al.
 2018/0176426 A1 6/2018 Wei et al.
 2018/0198897 A1 7/2018 Tang et al.
 2018/0241922 A1 8/2018 Baldwin et al.
 2018/0295292 A1 10/2018 Lee et al.
 2018/0300901 A1 10/2018 Wakai et al.
 2019/0121103 A1 4/2019 Bachar et al.

FOREIGN PATENT DOCUMENTS

CN 102739949 A 10/2012
 CN 103024272 A 4/2013
 CN 103841404 A 6/2014
 EP 1536633 A1 6/2005
 EP 1780567 A1 5/2007
 EP 2523450 A1 11/2012
 JP S59191146 A 10/1984
 JP 04211230 A 8/1992

JP H07318864 A 12/1995
 JP 08271976 A 10/1996
 JP 2002010276 A 1/2002
 JP 2003298920 A 10/2003
 JP 2004133054 A 4/2004
 JP 2004245982 A 9/2004
 JP 2005099265 A 4/2005
 JP 2006238325 A 9/2006
 JP 2007228006 A 9/2007
 JP 2007306282 A 11/2007
 JP 2008076485 A 4/2008
 JP 2010204341 A 9/2010
 JP 2011085666 A 4/2011
 JP 2013106289 A 5/2013
 KR 20070005946 A 1/2007
 KR 20090058229 A 6/2009
 KR 20100008936 A 1/2010
 KR 20140014787 A 2/2014
 KR 101477178 B1 12/2014
 KR 20140144126 A 12/2014
 KR 20150118012 A 10/2015
 WO 2000027131 A2 5/2000
 WO 2004084542 A1 9/2004
 WO 2006008805 A1 1/2006
 WO 2009097552 8/2009
 WO 2010122841 A1 10/2010
 WO 2014072818 A2 5/2014
 WO 2017025822 A1 2/2017
 WO 2017037688 A1 3/2017
 WO 2018130898 A1 7/2018

OTHER PUBLICATIONS

A 3MPixel Multi-Aperture Image Sensor with 0.7 μ m Pixels in 0.11 μ m CMOS, Fife et al., Stanford University, 2008, 3 pages.
 Dual camera intelligent sensor for high definition 360 degrees surveillance, Scotti et al., Publisher: IET, May 9, 2000, 8 pages.
 Dual-sensor foveated imaging system, Hua et al., Publisher: Optical Society of America, Jan. 14, 2008, 11 pages.
 Defocus Video Matting, McGuire et al., Publisher: ACM Siggraph, Jul. 31, 2005, 11 pages.
 Compact multi-aperture imaging with high angular resolution, Santacana et al., Publisher: Optical Society of America, 2015, 10 pages.
 Multi-Aperture Photography, Green et al., Publisher: Mitsubishi Electric Research Laboratories, Inc., Jul. 2007, 10 pages.
 Multispectral Bilateral Video Fusion, Bennett et al., Publisher: IEEE, May 2007, 10 pages.
 Super-resolution imaging using a camera array, Santacana et al., Publisher: Optical Society of America, 2014, 6 pages.
 Optical Splitting Trees for High-Precision Monocular Imaging, McGuire et al., Publisher: IEEE, 2007, 11 pages.
 High Performance Imaging Using Large Camera Arrays, Wilburn et al., Publisher: Association for Computing Machinery, Inc., 2005, 12 pages.
 Real-time Edge-Aware Image Processing with the Bilateral Grid, Chen et al., Publisher: ACM Siggraph, 2007, 9 pages.
 Superimposed multi-resolution imaging, Carles et al., Publisher: Optical Society of America, 2017, 13 pages.
 Viewfinder Alignment, Adams et al., Publisher: Eurographics, 2008, 10 pages.
 Dual-Camera System for Multi-Level Activity Recognition, Bodor et al., Publisher: IEEE, Oct. 2014, 6 pages.
 Engineered to the task: Why camera-phone cameras are different, Giles Humpston, Publisher: Solid State Technology, Jun. 2009, 3 pages.
 Office Action in related CN patent application No. 202110100089.9, dated Jul. 21, 2021.
 International Search Report and Written Opinion issued in related PCT patent application PCT/IB2013/060356, dated Apr. 17, 2014, 15 pages.

* cited by examiner

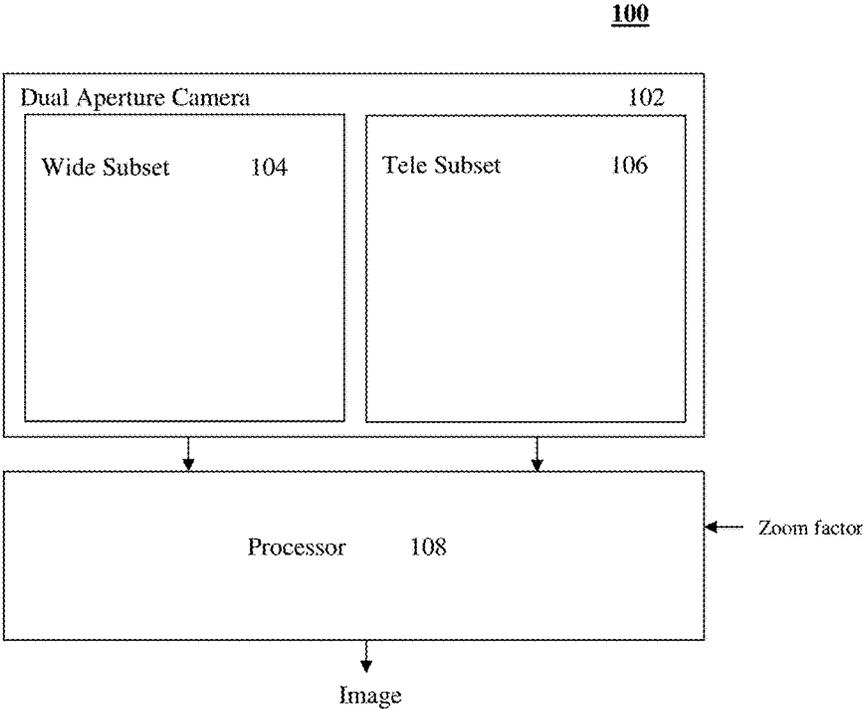


FIG. 1A

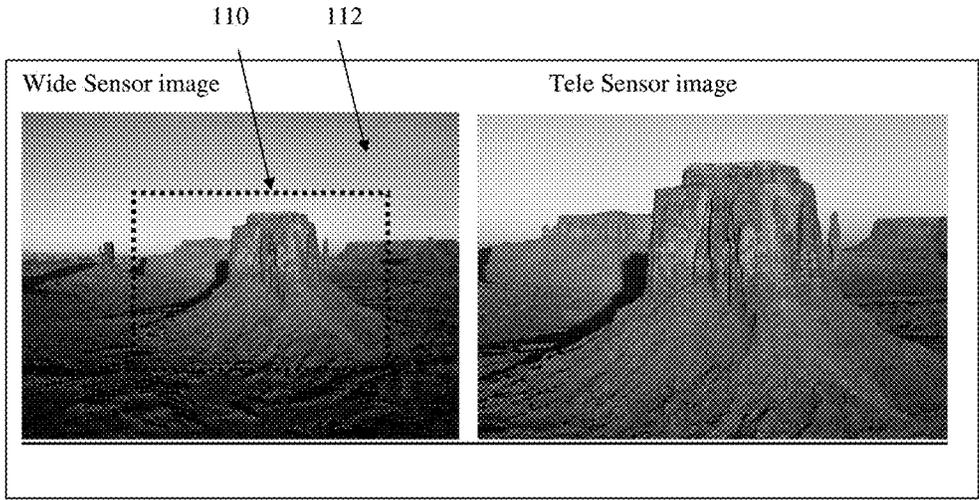


FIG. 1B

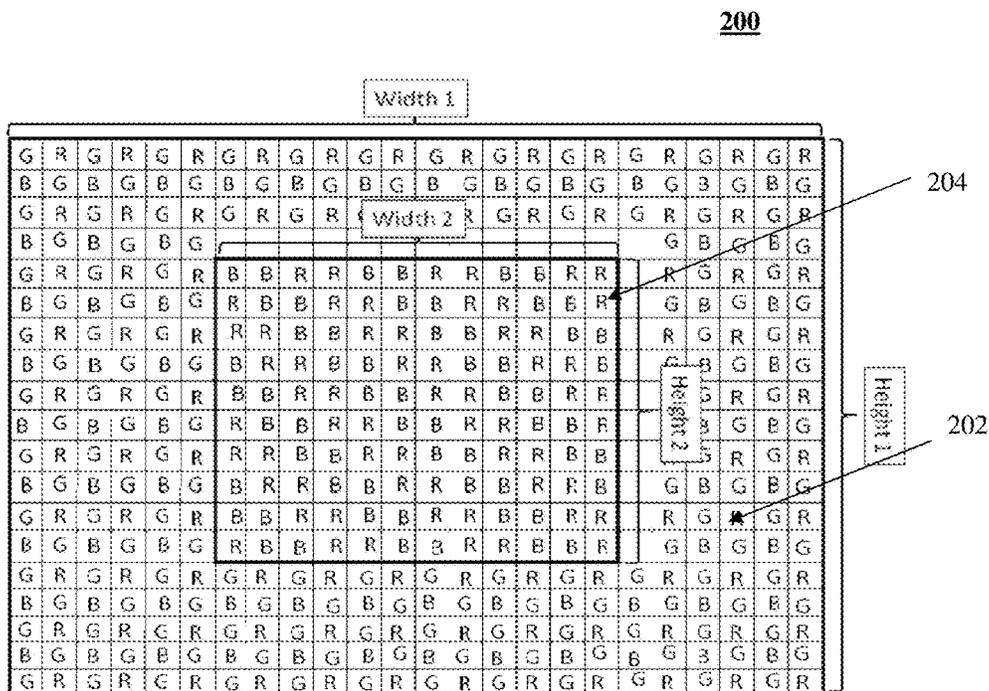


FIG. 2

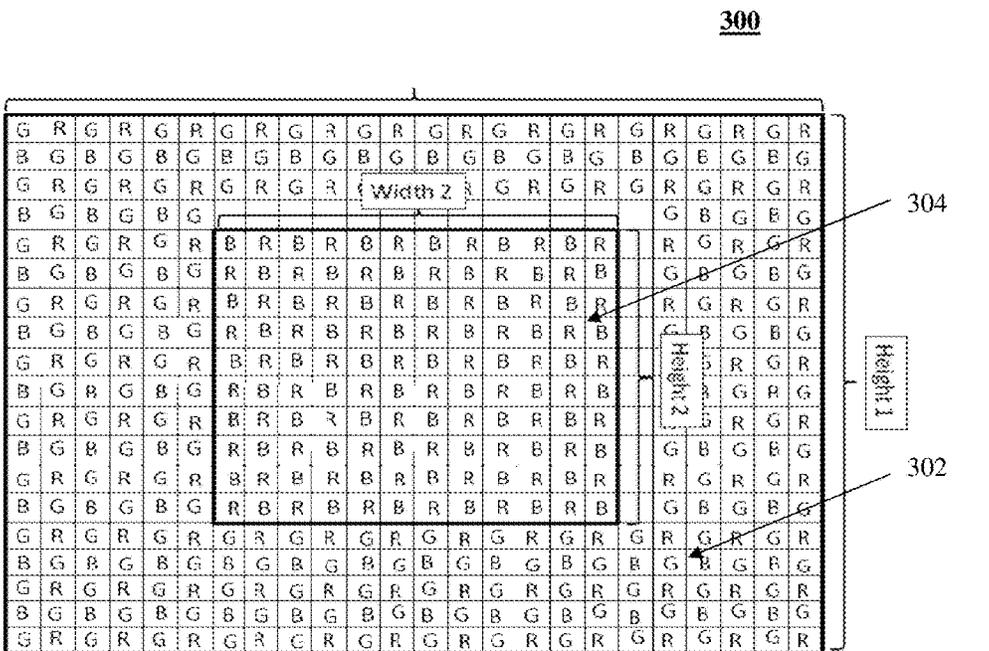


FIG. 3

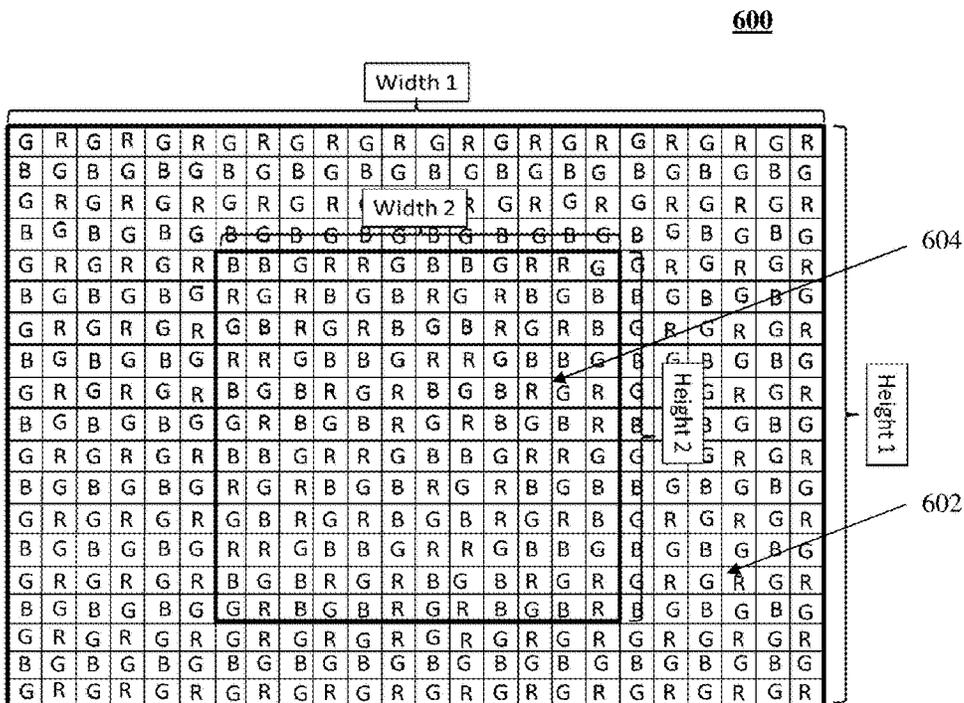


FIG. 6

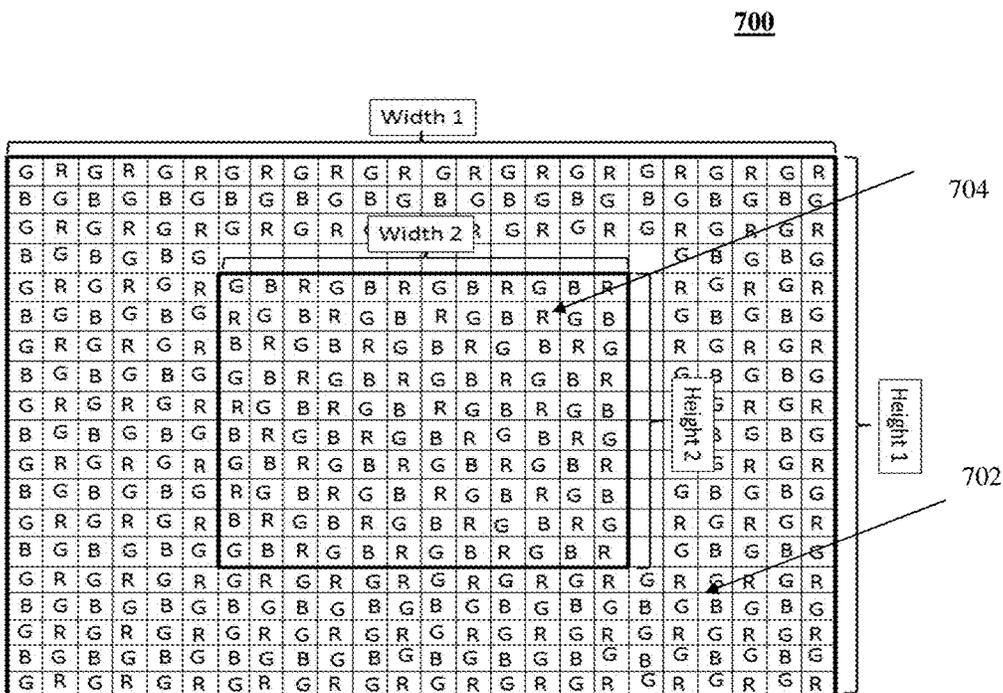


FIG. 7

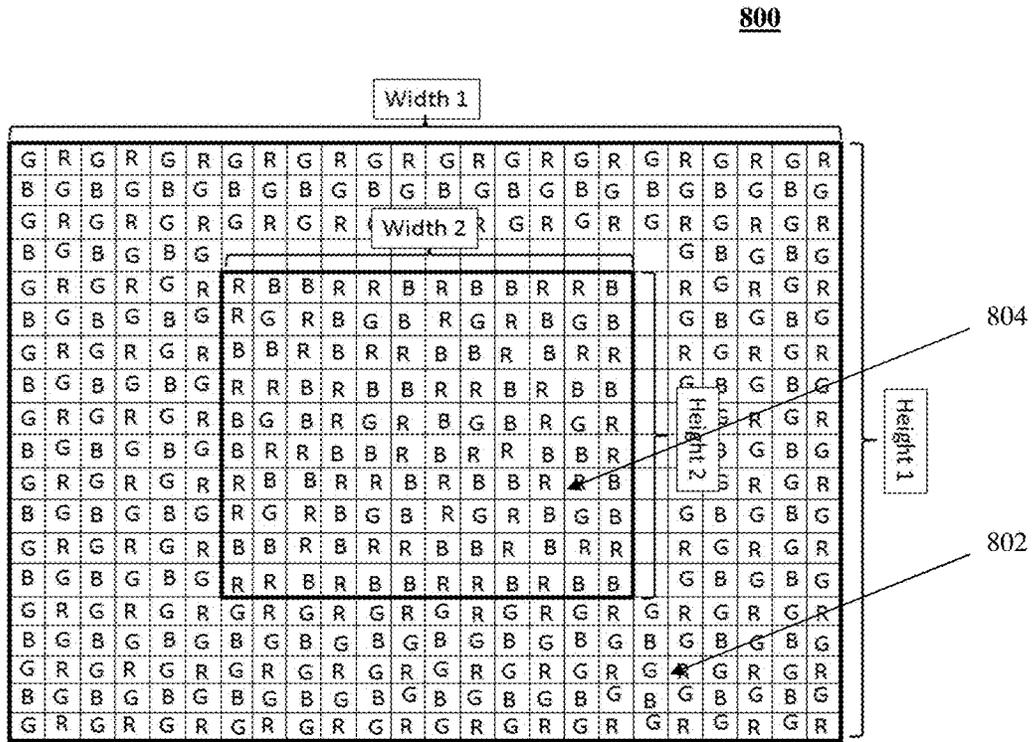


FIG. 8

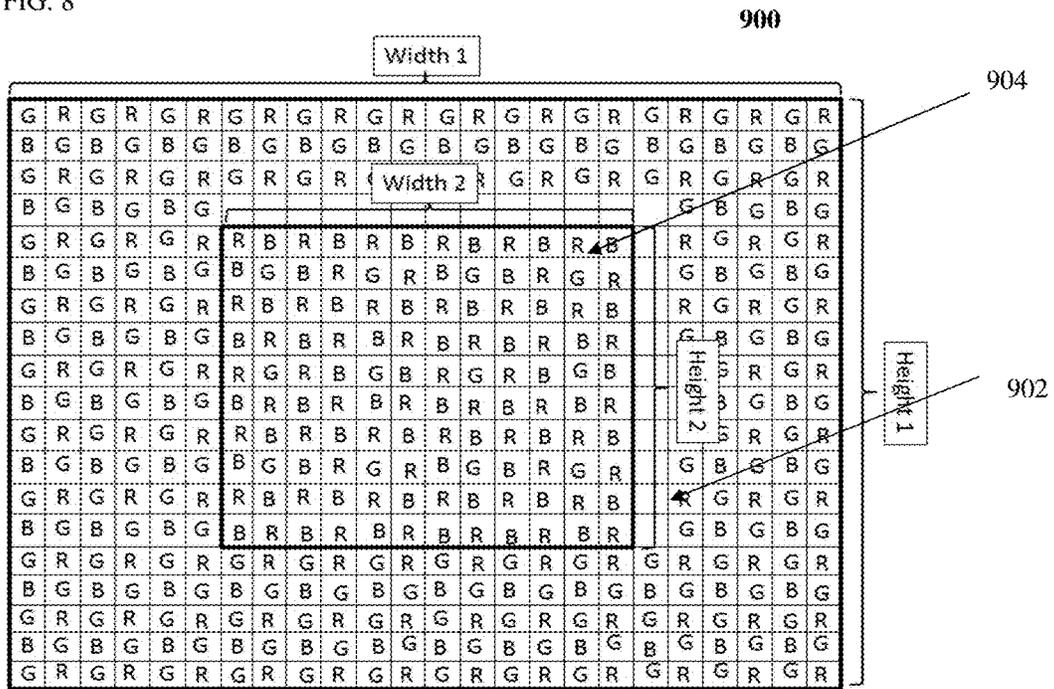


FIG. 9

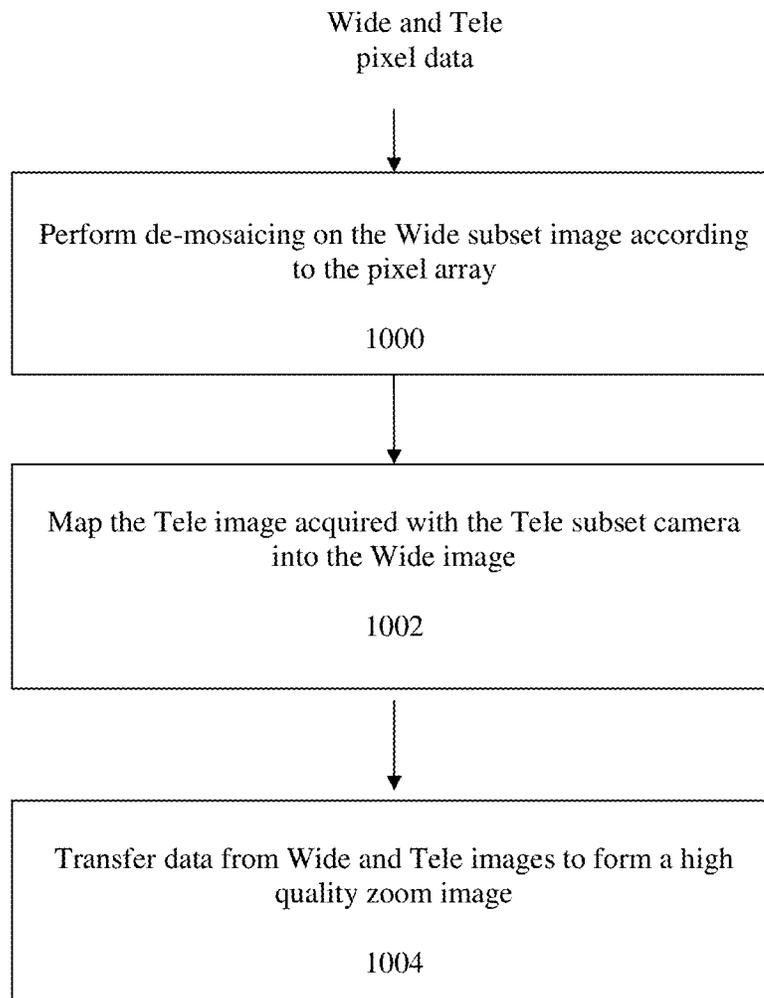


FIG. 10

1100

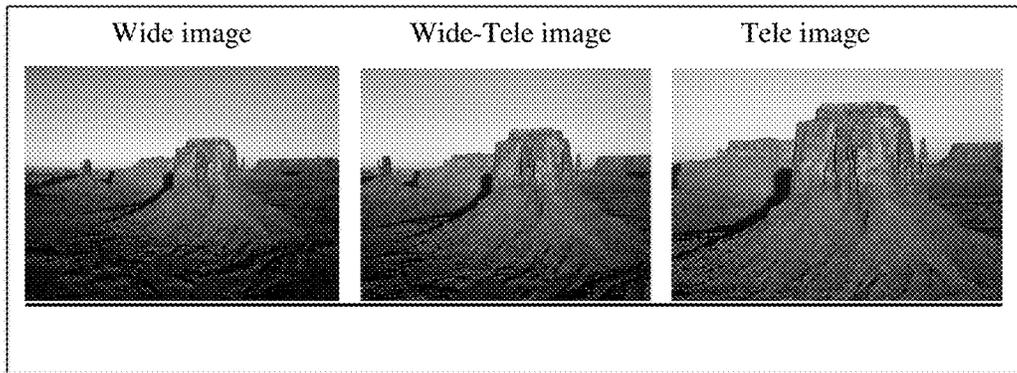
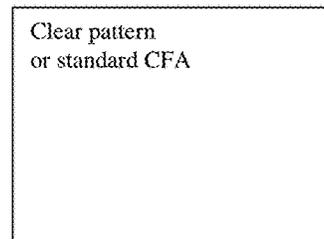
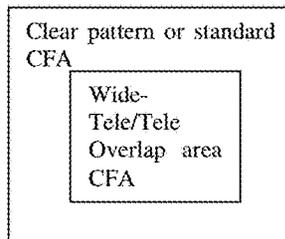
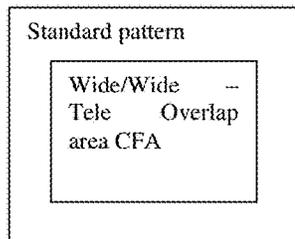


FIG. 11A

Wide sensor (X1)

Wide-Tele sensor (X1.5)

Tele sensor (X2)



1102

1104

1106

FIG. 11B

HIGH RESOLUTION THIN MULTI-APERTURE IMAGING SYSTEMS

Matter enclosed in heavy brackets [] appears in the original patent but forms no part of this reissue specification; matter printed in italics indicates the additions made by reissue; a claim printed with strikethrough indicates that the claim was canceled, disclaimed, or held invalid by a prior post-patent action or proceeding.

CROSS REFERENCE TO RELATED APPLICATIONS

[This application is a Continuation application of U.S. patent application Ser. No. 14/386,823 (now allowed), which was a National Phase application from PCT patent application PCT/IB2013/060356 which claimed priority from U.S. Provisional Patent Application No. 61/730,570 having the same title and filed Nov. 28, 2012, the latter incorporated herein by reference in its entirety.] *This broadening reissue application is a continuation of U.S. patent application Ser. No. 16/383,618, filed Apr. 14, 2019, now U.S. Pat. No. RE48,4544E, which is a reissue application of U.S. patent application Ser. No. 15/375,090, filed Dec. 11, 2016, now U.S. Pat. No. 9,876,952, which is a continuation of U.S. patent application Ser. No. 14/386,823, filed Apr. 22, 2014, now U.S. Pat. No. 9,538,152, which was a National Phase application from PCT application PCT/IB2013/060356 which claimed priority from U.S. Provisional Patent Application No. 61/730,570 having the same title and filed Nov. 28, 2012, the latter incorporated herein by reference in its entirety. The following three co-pending applications are also continuation reissue applications of U.S. patent application Ser. No. 16/383,618, filed Apr. 14, 2019: U.S. patent application Ser. No. 16/384,140, filed Apr. 15, 2019, U.S. patent application Ser. No. 16/384,197, filed Apr. 15, 2019, and U.S. patent application Ser. No. 16/384,244, filed Apr. 15, 2019.*

FIELD

Embodiments disclosed herein relate in general to multi-aperture imaging (“MAI”) systems (where “multi” refers to two or more apertures) and more specifically to thin MAI systems with high color resolution and/or optical zoom.

BACKGROUND

Small digital cameras integrated into mobile (cell) phones, personal digital assistants and music players are becoming ubiquitous. Each year, mobile phone manufacturers add more imaging features to their handsets, causing these mobile imaging devices to converge towards feature sets and image quality that customers expect from stand-alone digital still cameras. Concurrently, the size of these handsets is shrinking, making it necessary to reduce the total size of the camera accordingly while adding more imaging features. Optical Zoom is a primary feature of many digital still cameras but one that mobile phone cameras usually lack, mainly due to camera height constraints in mobile imaging devices, cost and mechanical reliability.

Mechanical zoom solutions are common in digital still cameras but are typically too thick for most camera phones. Furthermore, the F/# (“F number”) in such systems typically increases with the zoom factor (ZF) resulting in poor light sensitivity and higher noise (especially in low-light sce-

narios). In mobile cameras, this also results in resolution compromise, due to the small pixel size of their image sensors and the diffraction limit optics associated with the F/#.

One way of implementing zoom in mobile cameras is by over-sampling the image and cropping and interpolating it in accordance with the desired ZF. While this method is mechanically reliable, it results in thick optics and in an expensive image sensor due to the large number of pixels so associated therewith. As an example, if one is interested in implementing a 12 Megapixel camera with X3 ZF, one needs a sensor of 108 Megapixels.

Another way of implementing zoom, as well as increasing the output resolution, is by using a dual-aperture imaging (“DAI”) system. In its basic form, a DAI system includes two optical apertures which may be formed by one or two optical modules, and one or two image sensors (e.g., CMOS or CCD) that grab the optical image or images and convert the data into the electronic domain, where the image can be processed and stored.

The design of a thin MAI system with improved resolution requires a careful choice of parameters coupled with advanced signal processing algorithms to support the output of a high quality image. Known MAI systems, in particular ones with short optical paths, often trade-off functionalities and properties, for example zoom and color resolution, or image resolution and quality for camera module height. Therefore, there is a need for, and it would be advantageous to have thin MAI systems that produce an image with high resolution (and specifically high color resolution) together with zoom functionality.

Moreover, known signal processing algorithms used together with existing MAI systems often further degrade the output image quality by introducing artifacts when combining information from different apertures. A primary source of these artifacts is the image registration process, which has to find correspondences between the different images that are often captured by different sensors with different color filter arrays (CFAs). There is therefore a need for, and it would be advantageous to have an image registration algorithm that is more robust to the type of CFA used by the cameras and which can produce better correspondence between images captured by a multi-aperture system.

SUMMARY

Embodiments disclosed herein teach the use of multi-aperture imaging systems to implement thin cameras (with short optical paths of less than about 9 mm) and/or to realize optical zoom systems in such thin cameras. Embodiments disclosed herein further teach new color filter arrays that optimize the color information which may be achieved in a multi-aperture imaging system with or without zoom. In various embodiments, a MAI system disclosed herein includes at least two sensors or a single sensor divided into at least two areas. Hereinafter, the description refers to “two sensors”, with the understanding that they may represent sections of a single physical sensor (imager chip). Exemplarily, in a dual-aperture imaging system, a left sensor (or left side of a single sensor) captures an image coming from a first aperture while a right sensor (or right side of a single sensor) captures an image coming from a second aperture. In various embodiments disclosed herein, one sensor is a “Wide” sensor while another sensor is a “Tele” sensor, see e.g. FIG. 1A. The Wide sensor includes either a single standard CFA or two different CFAs: a non-standard CFA with higher color sampling rate positioned in an “overlap

area” of the sensor (see below description of FIG. 1B) and a standard CFA with a lower color sampling rate surrounding the overlap area. When including a single standard CFA, the CFA may cover the entire Wide sensor area. A “standard CFA” may include a RGB (Bayer) pattern or a non-Bayer pattern such as RGBE, CYYM, CYGM, RGBW#1, RGBW#2 or RGBW#3. Thus, reference may be made to “standard Bayer” or “standard non-Bayer” patterns or filters. As used herein, “non-standard CFA” refers to a CFA that is different in its pattern than CFAs listed above as “standard”. Exemplary non-standard CFA patterns may include repetitions of a 2x2 micro-cell in which the color filter order is RR-BB, RB-BR or YC-CY where Y=Yellow=Green+Red, C=Cyan=Green+Blue; repetitions of a 3x3 micro-cell in which the color filter order is GBR-GB-BRG; and repetitions of a 6x6 micro-cell in which the color filter order is RBBRRB-RWRBWB-BBRBRR-RRBRBB-BWBRWR-BRRBBR, or BBGRRG-RGRBGB-GBRGRB-RRGBBG-BGGRGR-GRBGBR, or RBBRRB-RGRBGB-BBRBRR-RRBRBB-BGBRGR-BRRBBR, or, RBRBRB-BGBRGR-RBRBRB-BRBRBR-RGRBGB-BRBRBR.

The Tele sensor may be a Clear sensor (i.e. a sensor without color filters) or a standard CFA sensor. This arrangement of the two (or more than two) sensors and of two (or more than two) Wide and Tele “subset cameras” (or simply “subsets”) related to the two Wide and Tele subsets. Each sensor provides a separate image (referred to respectively as a Wide image and a Tele image), except for the case of a single sensor, where two images are captured (grabbed) by the single sensor (example above). In some embodiments, zoom is achieved by fusing the two images, resulting in higher color resolution that approaches that of a high quality dual-aperture zoom camera. Some thin MAI systems disclosed herein therefore provide zoom, super-resolution, high dynamic range and enhanced user experience.

In some embodiments, in order to reach optical zoom capabilities, a different magnification image of the same scene is grabbed by each subset, resulting in field of view (FOV) overlap between the two subsets. In some embodiments, the two subsets have the same zoom (i.e. same FOV). In some embodiments, the Tele subset is the higher zoom subset and the Wide subset is the lower zoom subset. Post processing is applied on the two images grabbed by the MAI system to fuse and output one fused (combined) output zoom image processed according to a user ZF input request. In some embodiments, the resolution of the fused image may be higher than the resolution of the Wide/Tele sensors. As part of the fusion procedure, up-sampling may be applied on the Wide image to scale it to the Tele image.

In an embodiment there is provided a multi-aperture imaging system comprising a first camera subset that provides a first image, the first camera subset having a first sensor with a first plurality of sensor pixels covered at least in part with a non-standard CFA, the non-standard CFA used to increase a specific color sampling rate relative to a same color sampling rate in a standard CFA; a second camera subset that provides a second image, the second camera subset having a second sensor with a second plurality of sensor pixels either Clear or covered with a standard CFA; and a processor configured to process the first and second images into a combined output image.

In some embodiments, the first and the second camera subsets have identical FOVs and the non-standard CFA may cover an overlap area that includes all the pixels of first sensor, thereby providing increased color resolution. In some such embodiments, the processor is further configured to, during the processing of the first and second images into

a combined output image, register respective first and second Luma images obtained from the first and second images, the registered first and second Luma images used together with color information to form the combined output image.

5 In an embodiment, the registration includes finding a corresponding pixel in the second Luma image for each pixel in the first Luma image, whereby the output image is formed by transferring information from the second image to the first image. In another embodiment, the registration includes finding a corresponding pixel in the first Luma image for each pixel in the second Luma image, whereby the output image is formed by transferring information from the first image to the second image.

In some embodiments, the first camera subset has a first FOV, the second camera subset has a second, smaller FOV than the first FOV, and the non-standard CFA covers an overlap area on the first sensor that captures the second FOV, thereby providing both optical zoom and increased color resolution. In some such embodiments, the processor is further configured to, during the processing of the first and second images into a combined output image and based on a ZF input, register respective first and second Luma images obtained from the first and second images, the registered first and second Luma images used together with color information to form the combined output image. For a ZF input that defines an FOV greater than the second FOV, the registration includes finding a corresponding pixel in the second Luma image for each pixel in the first Luma image and the processing includes forming the output image by transferring information from the second image to the first image. For a ZF input that defines an FOV smaller than or equal to the second FOV, the registration includes finding a corresponding pixel in the first Luma image for each pixel in the second Luma image, and the processing includes forming the output image by transferring information from the first image to the second image.

In an embodiment there is provided a multi-aperture imaging system comprising a first camera subset that provides a first image, the first camera subset having a first sensor with a first plurality of sensor pixels covered at least in part with a standard CFA; a second camera subset that provides a second image, the second camera subset having a second sensor with a second plurality of sensor pixels either Clear or covered with a standard CFA; and a processor configured to register first and second Luma images obtained respectively from the first and second images and to process the registered first and second Luma images together with color information into a combined output image.

50 In some embodiments, the first and the second camera subsets have identical first and second FOVs. In some such embodiments, the registration includes finding a corresponding pixel in the second Luma image for each pixel in the first Luma image and the processing includes forming the output image by transferring information from the second image to the first image. In other such embodiments, the registration includes finding a corresponding pixel in the first Luma image for each pixel in the second Luma image and the processing includes forming the output image by transferring information from the first image to the second image.

In some embodiments, the first camera subset has a first FOV, the second camera subset has a second, smaller FOV than the first FOV, and the processor is further configured to register the first and second Luma images based on a ZF input. For a ZF input that defines an FOV greater than the second FOV, the registration includes finding a corresponding pixel in the second Luma image for each pixel in the first

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Luma image and the processing includes forming the output image by transferring information from the second image to the first image. For a ZF input that defines an FOV smaller than or equal to the second FOV, the registration includes finding a corresponding pixel in the first Luma image for each pixel in the second Luma image, and the processing includes forming the output image by transferring information from the first image to the second image.

BRIEF DESCRIPTION OF THE DRAWINGS

Non-limiting examples of embodiments disclosed herein are described below with reference to figures attached hereto that are listed following this paragraph. The drawings and descriptions are meant to illuminate and clarify embodiments disclosed herein, and should not be considered limiting in any way.

FIG. 1A shows schematically a block diagram illustrating a dual-aperture zoom imaging system disclosed herein;

FIG. 1B shows an example of an image captured by the Wide sensor and the Tele sensor while illustrating the overlap area on the Wide sensor;

FIG. 2 shows schematically an embodiment of a Wide sensor that may be implemented in a dual-aperture zoom imaging system disclosed herein;

FIG. 3 shows schematically another embodiment of a Wide camera sensor that may be implemented in a dual-aperture zoom imaging system disclosed herein;

FIG. 4 shows schematically yet another embodiment of a Wide camera sensor that may be implemented in a dual-aperture zoom imaging system disclosed herein;

FIG. 5 shows schematically yet another embodiment of a Wide camera sensor that may be implemented in a dual-aperture zoom imaging system disclosed herein;

FIG. 6 shows schematically yet another embodiment of a Wide camera sensor that may be implemented in a dual-aperture zoom imaging system disclosed herein;

FIG. 7 shows schematically yet another embodiment of a Wide camera sensor that may be implemented in a dual-aperture zoom imaging system disclosed herein;

FIG. 8 shows schematically yet another embodiment of a Wide camera sensor that may be implemented in a dual-aperture zoom imaging system disclosed herein;

FIG. 9 shows schematically yet another embodiment of a Wide camera sensor that may be implemented in a dual-aperture zoom imaging system disclosed herein;

FIG. 10 shows a schematically in a flow chart an embodiment of a method disclosed herein for acquiring and outputting a zoom image;

FIG. 11A shows exemplary images captured by a triple aperture zoom imaging system disclosed herein;

FIG. 11B illustrates schematically the three sensors of the triple aperture imaging system of FIG. 11A.

DETAILED DESCRIPTION

Embodiments disclosed herein relate to multi-aperture imaging systems that include at least one Wide sensor with a single CFA or with two different CFAs and at least one Tele sensor. The description continues with particular reference to dual-aperture imaging systems that include two (Wide and Tele) subsets with respective sensors. A three-aperture imaging system is described later with reference to FIGS. 11A-11B.

The Wide sensor includes an overlap area (see description of FIG. 1B) that captures the Tele FOV. The overlap area may cover the entire Wide sensor or only part of the sensor.

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The overlap area may include a standard CFA or a non-standard CFA. Since the Tele image is optically magnified compared to the Wide image, the effective sampling rate of the Tele image is higher than that of the Wide image. Thus, the effective color sampling rate in the Wide sensor is much lower than the Clear sampling rate in the Tele sensor. In addition, the Tele and Wide images fusion procedure (see below) requires up-scaling of the color data from the Wide sensor. Up-scaling will not improve color resolution. In some applications, it is therefore advantageous to use a non-standard CFA in the Wide overlap area that increases color resolution for cases in which the Tele sensor includes only Clear pixels. In some embodiments in which the Tele sensor includes a Bayer CFA, the Wide sensor may have a Bayer CFA in the overlap area. In such embodiments, color resolution improvement depends on using color information from the Tele sensor in the fused output image.

FIG. 1A shows schematically a block diagram illustrating a dual-aperture zoom imaging (“DAZI”) system **100** disclosed herein. System **100** includes a dual-aperture camera **102** with a Wide subset **104** and a Tele subset **106** (each subset having a respective sensor), and a processor **108** that fuses two images, a Wide image obtained with the Wide subset and a Tele image obtained with the Tele subset, into a single fused output image according to a user-defined “applied” ZF input or request. The ZF is input to processor **108**. The Wide sensor may include a non-standard CFA in an overlap area illustrated by **110** in FIG. 1B. Overlap area **110** is surrounded by a non-overlap area **112** with a standard CFA (for example a Bayer pattern). FIG. 1B also shows an example of an image captured by both Wide and Tele sensors. Note that “overlap” and “non-overlap” areas refer to parts of the Wide image as well as to the CFA arrangements of the Wide sensor. The overlap area may cover different portions of a Wide sensor, for example half the sensor area, a third of the sensor area, a quarter of the sensor area, etc. A number of such Wide sensor CFA arrangements are described in more detail with reference to FIGS. 2-9. The non-standard CFA pattern increases the color resolution of the DAZI system.

The Tele sensor may be Clear (providing a Tele Clear image scaled relative to the Wide image) or may include a standard (Bayer or non-Bayer) CFA. It in the latter case, it is desirable to define primary and auxiliary sensors based on the applied ZF. If the ZF is such that the output FOV is larger than the Tele FOV, the primary sensor is the Wide sensor and the auxiliary sensor is the Tele sensor. If the ZF is such that the output FOV is equal to, or smaller than the Tele FOV, the primary sensor is the Tele sensor and the auxiliary sensor is the Wide sensor. The point of view defined by the output image is that of the primary sensor.

FIG. 2 shows schematically an embodiment of a Wide sensor **200** that may be implemented in a DAZI system such as system **100**. Sensor **200** has a non-overlap area **202** with a Bayer CFA and an overlap area **204** covered by a non-standard CFA with a repetition of a 4×4 micro-cell in which the color filter order is BBRR-RBBR-RRBB-BRRB. In this figure, as well as in FIGS. 3-9, “Width 1” and “Height 1” refer to the full Wide sensor dimension. “Width 2” and “Height 2” refer to the dimensions of the Wide sensor overlap area. Note that in FIG. 2 (as in following FIGS. 3-5 and 7, 8) the empty row and column to the left and top of the overlap area are for clarity purposes only, and that the sensor pixels follow there the pattern of the non-overlap area (as shown in FIG. 6). In overlap area **204**, R and B are sampled at $\frac{1}{2}^{0.5}$ Nyquist frequency in the diagonal (left to right)

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direction with 2 pixel intervals instead of at $\frac{1}{2}$ Nyquist frequency in a standard Bayer pattern.

FIG. 3 shows schematically an embodiment of a Wide sensor 300 that may be implemented in a DAZI system such as system 100. Sensor 300 has a non-overlap area 302 with a Bayer CFA and an overlap area 304 covered by a non-standard CFA with a repetition of a 2×2 micro-cell in which the color filter order is BR-RB. In the overlap area, R and B are sampled at $\frac{1}{2}^{0.5}$ Nyquist frequency in both diagonal directions.

FIG. 4 shows schematically an embodiment of a Wide sensor 400 that may be implemented in a DAZI system such as system 100. Sensor 400 has a non-overlap area 402 with a Bayer CFA and an overlap area 404 covered by a non-standard CFA with a repetition of a 2×2 micro-cell in which the color filter order is YC-CY, where Y=Yellow=Green+Red, C=Cyan=Green+Blue. As a result, in the overlap area, R and B are sampled at $\frac{1}{2}^{0.5}$ Nyquist frequency in a diagonal direction. The non-standard CFA includes green information for registration purposes. This allows for example registration between the two images where the object is green, since there is green information in both sensor images.

FIG. 5 shows schematically an embodiment of a Wide sensor 500 that may be implemented in a DAZI system such as system 100. Sensor 500 has a non-overlap area 502 with a Bayer CFA and an overlap area 504 covered by a non-standard CFA with a repetition of a 6×6 micro-cell in which the color filter order is RBBRRB-RWRBWB-BBRBRR-RRBRBB-BWBRWR-BRRBBR, where "W" represents White or Clear pixels. In the overlap area, R and B are sampled at a higher frequency than in a standard CFA. For example, in a Bayer pixel order, the Red average sampling rate ("R_s") is 0.25 (sampled once for every 4 pixels). In the overlap area pattern, R_s is 0.44.

FIG. 6 shows schematically an embodiment of a Wide sensor 600 that may be implemented in a DAZI system such as system 100. Sensor 600 has a non-overlap area 602 with a Bayer CFA and an overlap area 604 covered by a non-standard CFA with a repetition of a 6×6 micro-cell in which the color filter order is BBGRRG-RGRBGB-GBRGRB-RRGBBG-BGBRGR-GRBGBR. In the overlap area, R and B are sampled at a higher frequency than in a standard CFA. For example, in the overlap area pattern, R_s is 0.33 vs. 0.25 in a Bayer pixel order.

FIG. 7 shows schematically an embodiment of a Wide sensor 700 that may be implemented in a DAZI system such as system 100. Sensor 700 has a non-overlap area 702 with a Bayer CFA and an overlap area 704 covered by a non-standard CFA with a repetition of a 3×3 micro-cell in which the color filter order is GBR-RGB-BRG. In the overlap area, R and B are sampled at a higher frequency than in a standard CFA. For example, in the overlap area pattern, R_s is 0.33 vs. 0.25 in a Bayer pixel order.

FIG. 8 shows schematically an embodiment of a Wide sensor 800 that may be implemented in a DAZI system such as system 100. Sensor 800 has a non-overlap area 802 with a Bayer CFA and an overlap area 804 covered by a non-standard CFA with a repetition of a 6×6 micro-cell in which the color filter order is RBBRRB-RGRBGB-BBRBRR-RRBRBB-BGBRGR-BRRBBR. In the overlap area, R and B are sampled at a higher frequency than in a standard CFA. For example, in the overlap area pattern, R_s is 0.44 vs. 0.25 in a Bayer pixel order.

FIG. 9 shows schematically an embodiment of a Wide sensor 900 that may be implemented in a DAZI system such as system 100. Sensor 900 has a non-overlap area 902 with a Bayer CFA and an overlap area 904 covered by a non-

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standard CFA with a repetition of a 6×6 micro-cell in which the color filter order is RBRBRB-BGGRGR-RBRBRB-BRBRBR-RGRBGB-BRBRBR. In the overlap area, R and B are sampled at a higher frequency than in a standard CFA. For example, in the overlap area pattern, R_s is 0.44 vs. 0.25 in a Bayer pixel order.

Processing Flow

In use, an image is acquired with imaging system 100 and is processed according to steps illustrated in a flowchart shown in FIG. 10. In step 1000, demosaicing is performed on the Wide overlap area pixels (which refer to the Tele image FOV) according to the specific CFA pattern. If the CFA in the Wide overlap area is a standard CFA, a standard demosaicing process may be applied to it. If the CFA in the Wide overlap area is non-standard CFA, the overlap and non-overlap subsets of pixels may need different demosaicing processes. That is, the Wide overlap area may need a non-standard demosaicing process and the Wide non-overlap area may need a standard demosaicing process. Exemplary and non-limiting non-standard demosaicing interpolations for the overlap area of each of the Wide sensors shown in FIGS. 2-9 are given in detail below. The aim of the demosaicing is to reconstruct missing colors in each pixel. Demosaicing is applied also to the Tele sensor pixels if the Tele sensor is not a Clear only sensor. This will result in a Wide subset color image where the colors (in the overlap area) hold higher resolution than those of a standard CFA pattern. In step 1002, the Tele image is registered (mapped) into the Wide image. The mapping includes finding correspondences between pixels in the two images. In step 1002, actual registration is performed on luminance Tele and Wide images (respectively Luma_{Tele} and Luma_{Wide}) calculated from the pixel information of the Tele and Wide cameras. These luminance images are estimates for the scene luminance as captured by each camera and do not include any color information. If the Wide or Tele sensors have CFAs, the calculation of the luminance images is performed on the respective demosaiced images. The calculation of the Wide luminance image varies according to the type of non-standard CFA used in the Wide overlap area. If the CFA permits calculation of a full RGB demosaiced image, the luminance image calculation is straightforward. If the CFA is such that it does not permit calculation of a full RGB demosaiced image, the luminance image is estimated from the available color channels. If the Tele sensor is a Clear sensor, the Tele luminance image is just the pixel information. Performing the registration on luminance images has the advantage of enabling registration between images captured by sensors with different CFAs or between images captured by a standard CFA or non-standard CFA sensor and a standard CFA or Clear sensor and avoiding color artifacts that may arise from erroneous registration.

In step 1004, the data from the Wide and Tele images is processed together with the registration information from step 1002 to form a high quality output zoom image. In cases where the Tele sensor is a Clear only sensor, the high resolution luminance component is taken from the Tele sensor and color resolution is taken from the Wide sensor. In cases where the Tele sensor includes a CFA, both color and luminance data are taken from the Tele subset to form the high quality zoom image. In addition, color and luminance data is taken from the Wide subset.

Exemplary Process for Fusing a Zoom Image

1. Special Demosaicing

In this step, the Wide image is interpolated to reconstruct the missing pixel values. Standard demosaicing is applied in the non-overlap area. If the overlap area includes a standard

CFA, standard demosaicing is applied there as well. If the overlap area includes a non-standard CFA, a special demosaicing algorithm is applied, depending on the CFA pattern used. In addition, in case the Tele sensor has a CFA, standard demosaicing is applied to reconstruct the missing pixel values in each pixel location and to generate a full RGB color image.

2. Registration Preparation

Tele image: a luminance image $Luma_{Tele}$ is calculated from the Tele sensor pixels. If the Tele subset has a Clear sensor, $Luma_{Tele}$ is simply the sensor pixels data. If the Tele subset has a standard CFA, $Luma_{Tele}$ is calculated from the demosaiced Tele image.

Wide image: as a first step, in case the Wide overlap CFA permits estimating the luminance component of the image, the luminance component is calculated from the demosaiced Wide image, $Luma_{Wide}$. If the CFA is one of those depicted in FIGS. 4-9, a luminance image is calculated first. If the CFA is one of the CFAs depicted in FIG. 2 or FIG. 3, a luminance image is not calculated. Instead, the following registration step is performed between a weighted average of the demosaiced channels of the Wide image and $Luma_{Tele}$. For convenience, this weighted average image is also denoted $Luma_{Wide}$. For example, if the Wide sensor CFA in the overlap region is as shown in FIG. 2, the demosaiced channels R_{Wide} and B_{Wide} are averaged to create $Luma_{Wide}$ according to $Luma_{Wide}=(f1*R_{Wide}+f2*B_{Wide})/(f1+f2)$, where $f1$ may be $f1=1$ and $f2$ may be $f2=1$.

Low-pass filtering is applied on the Tele luminance image in order to match its spatial frequency content to that of the $Luma_{Wide}$ image. This improves the registration performance, as after low-pass filtering the luminance images become more similar. The calculation is $Luma_{Tele} \rightarrow \text{Low pass filter} \rightarrow Luma_{Tele}^{LP}$, where "LP" denotes an image after low pass filtering.

3. Registration of $Luma_{Wide}$ and $Luma_{Tele}^{LP}$

This step of the algorithm calculates the mapping between the overlap areas in the two luminance images. The registration step does not depend on the type of CFA used (or the lack thereof), as it is applied on luminance images. The same registration step can therefore be applied on Wide and Tele images captured by standard CFA sensors, as well as by any combination of CFAs or Clear sensor pixels disclosed herein. The registration process chooses either the Wide image or the Tele image to be a primary image. The other image is defined as an auxiliary image. The registration process considers the primary image as the baseline image and registers the overlap area in the auxiliary image to it, by finding for each pixel in the overlap area of the primary image its corresponding pixel in the auxiliary image. The output image point of view is determined according to the primary image point of view (camera angle). Various correspondence metrics could be used for this purpose, among which are a sum of absolute differences and correlation.

In an embodiment, the choice of the Wide image or the Tele image as the primary and auxiliary images is based on the ZF chosen for the output image. If the chosen ZF is larger than the ratio between the focal-lengths of the Tele and Wide cameras, the Tele image is set to be the primary image and the Wide image is set to be the auxiliary image. If the chosen ZF is smaller than or equal to the ratio between the focal-lengths of the Tele and Wide cameras, the Wide image is set to be the primary image and the Tele image is set to be the auxiliary image. In another embodiment independent of a zoom factor, the Wide image is always the

primary image and the Tele image is always the auxiliary image. The output of the registration stage is a map relating Wide image pixels indices to matching Tele image pixels indices.

4. Combination into a High Resolution Image

In this final step, the primary and auxiliary images are used to produce a high resolution image. One can distinguish between several cases:

a. If the Wide image is the primary image, and the Tele image was generated from a Clear sensor, $Luma_{Wide}$ is calculated and replaced or averaged with $Luma_{Tele}$ in the overlap area between the two images to create a luminance output image, matching corresponding pixels according to the registration map $Luma_{Out}=c1*Luma_{Wide}+c2*Luma_{Tele}$. The values of $c1$ and $c2$ may change between different pixels in the image. Then, RGB values of the output are calculated from $Luma_{Out}$ and R_{Wide} , G_{Wide} , and B_{Wide} .

b. If the Wide image is the primary image and the Tele image was generated from a CFA sensor, $Luma_{Tele}$ is calculated and is combined with $Luma_{Wide}$ in the overlap area between the two images, according to the flow described in 4a.

c. If the Tele image is the primary image generated from a Clear sensor, the RGB values of the output are calculated from the $Luma_{Tele}$ image and R_{Wide} , G_{Wide} , and B_{Wide} (matching pixels according to the registration map).

d. If the Tele image is the primary image generated from a CFA sensor, the RGB values of the output (matching pixels according to the registration map) are calculated either by using only the Tele image data, or by also combining data from the Wide image. The choice depends on the zoom factor.

Certain portions of the registered Wide and Tele images are used to generate the output image based on the ZF of the output image. In an embodiment, if the ZF of the output image defines a FOV smaller than the Tele FOV, the fused high resolution image is cropped to the required field of view and digital interpolation is applied to scale up the image to the required output image resolution.

Exemplary and Non-Limiting Pixel Interpolations Specifications for the Overlap Area

FIG. 2

B11	B12	R13
R21	B22	B23
R31	R32	B33

In order to reconstruct the missing R22 pixel, we perform $R22=(R31+R13)/2$. The same operation is performed for all missing Blue pixels.

FIG. 3

R11	B12	R13
B21	R22	B23
R31	B32	R33

In order to reconstruct the missing B22 pixel, we perform $B22=(B12+B21+B32+B23)/4$. The same operation is performed for all missing Red pixels.

FIG. 4

Y11	C12	Y13
C21	Y22	C23
Y31	C32	Y33

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In order to reconstruct the missing C22 pixel, we perform $C22=(C12+C21+C32+C23)/4$. The same operation is performed for all missing Yellow pixels.

FIG. 5

Case 1: W is Center Pixel

R11	B12	B13
R21	W22	R23
B31	B32	R33

In order to reconstruct the missing 22 pixels, we perform the following:

$$B22=(B12+B32)/2$$

$$R22=(R21+R23)/2$$

$G22=(W22-R22-B22)$ (assuming that W includes the same amount of R, G and B colors).

Case 2: R22 is Center Pixel

B11	B12	R13	R14
W21	R22	B23	W24
B31	R32	B33	R34

$$B22=(B11+R33)/2$$

In order to reconstruct the missing 22 pixels, we perform the following:

$$W22=(2*W21+W24)/3$$

$G22=(W22-R22-B22)$ (assuming that W contains the same amount of R, G and B colors). The same operation is performed for Blue as the center pixel.

FIG. 6

B11	B12	G13	R14
R21	G22	R23	B24
G31	B32	R33	G34
R41	R42	G43	B44

In order to reconstruct the missing 22 pixels, we perform the following:

$$B22=(B12+B32)/2$$

$$R22=(R21+R23)/2$$

In order to reconstruct the missing 32 pixels, we perform the following:

$$G32=(2*G31+2*G22+G43)/5$$

$$R32=(R41+2*R42+2*R33+R23+R21)/7$$

FIG. 7

G11	B12	R13	G14
R21	G22	B23	R24
B31	R32	G33	B34
G41	B42	R43	G44

In order to reconstruct the missing 22 pixels, we perform the following:

$$B22=(2*B12+2*B23+B31)/5$$

$$R22=(2*R21+2*R32+R13)/5$$

and similarly for all other missing pixels.

FIG. 8

R11	B12	B13	R14
R21	G22	R23	B24
B31	B32	R33	B34
R41	R42	B43	R44
B51	G52	B53	R54

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In order to reconstruct the missing 22 pixels, we perform the following:

$$B22=(2*B12+2*B32+B13)/5$$

$$R22=(2*R21+2*R23+R11)/5$$

5 In order to reconstruct the missing 32 pixels, we perform the following:

$$G32=(2*G22+G52)/3$$

$$R32=(2*R33+2*R42+R41+R21+R23)/7$$

FIG. 9

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R11	B12	R13	B14
B21	G22	B23	R24
R31	B32	R33	B34
B41	R42	B43	R44
R51	G52	R53	B54

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In order to reconstruct the missing 22 pixels, we perform the following:

$$B22=(B12+B32+B23+B21)/4$$

$$R22=(R11+R13+R31+R33)/4$$

In order to reconstruct the missing 32 pixels, we perform the following:

$$G32=(2*G22+G52)/3$$

$$R32=(R42+R31+R33)/3$$

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Triple-Aperture Zoom Imaging System with Improved Color Resolution

As mentioned, a multi-aperture zoom or non-zoom imaging system disclosed herein may include more than two apertures. A non-limiting and exemplary embodiment **1100** of a triple-aperture imaging system is shown in FIGS. **11A-11B**. System **1100** includes a first Wide subset camera **1102** (with exemplarily X1), a second Wide subset camera (with exemplarily X1.5, and referred to as a "Wide-Tele" subset) and a Tele subset camera (with exemplarily X2). FIG. **11A** shows exemplary images captured by imaging system **1100**, while FIG. **11B** illustrates schematically three sensors marked **1102**, **1104** and **1106**, which belong respectively to the Wide, Wide-Tele and Tele subsets. FIG. **11B** also shows the CFA arrangements in each sensor: sensors **1102** and **1104** are similar to Wide sensors described above with reference to any of FIGS. **2-9**, in the sense that they include an overlap area and a non-overlap area. The overlap area includes a non-standard CFA. In both Wide sensors, the non-overlap area may have a Clear pattern or a standard CFA. Thus, neither Wide subset is solely a Clear channel camera. The Tele sensor may be Clear or have a standard Bayer CFA or a standard non-Bayer CFA. In use, an image is acquired with imaging system **1100** and processed as follows: demosaicing is performed on the overlap area pixels of the Wide and Wide-Tele sensors according to the specific CFA pattern in each overlap area. The overlap and non-overlap subsets of pixels in each of these sensors may need different demosaicing. Exemplary and non-limiting demosaicing specifications for the overlap area for Wide sensors shown in FIGS. **2-9** are given above. The aim is to reconstruct the missing colors in each and every pixel. In cases in which the Tele subset sensor is not Clear only, demosaicing is performed as well. The Wide and Wide-Tele subset color images acquired this way will have colors (in the overlap area) holding higher resolution than that of a standard CFA pattern. Then, the Tele image acquired with the Tele sensor is registered (mapped) into the respective Wide image. The data from the Wide, Wide-Tele and Tele images is then processed to form a high quality zoom image. In cases where the Tele subset is Clear only, high Luma resolution is taken from the Tele sensor and color resolution

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is taken from the Wide sensor. In cases where the Tele subset includes a CFA, both color and Luma resolution is taken from the Tele subset. In addition, color resolution is taken from the Wide sensor. The resolution of the fused image may be higher than the resolution of both sensors.

While this disclosure has been described in terms of certain embodiments and generally associated methods, alterations and permutations of the embodiments and methods will be apparent to those skilled in the art. For example, multi-aperture imaging systems with more than two Wide or Wide-Tele subsets (and sensors) or with more than one Tele subset (and sensor) may be constructed and used according to principles set forth herein. Similarly, non-zoom multi-aperture imaging systems with more than two sensors, at least one of which has a non-standard CFA, may be constructed and used according to principles set forth herein. The disclosure is to be understood as not limited by the specific embodiments described herein, but only by the scope of the appended claims.

What is claimed is:

[1. A multi-aperture imaging system comprising:

- a) a first camera that provides a first camera image, the first camera having a first sensor with a first plurality of sensor pixels covered at least in part with a non-standard color filter array (CFA) used to increase a specific color sampling rate relative to a same color sampling rate in a standard CFA, wherein the non-standard CFA includes a repetition of a $n \times n$ micro-cell where $n=4$ and wherein each micro-cell includes a BBRR-RBBR-RRBB-BRRB color filter order;
- b) a second camera that provides a second camera image, the second camera having a second sensor with a second plurality of sensor pixels, the second plurality of sensor pixels being either Clear or covered with a standard CFA, wherein the second camera image has an overlap area with the first camera image; and
- c) a processor configured to process the first and second camera images into a fused output image, wherein in the overlap area pixels of the second camera image are registered with corresponding pixels of the first camera image.]

[2. A multi-aperture imaging system comprising:

- a) a first camera that provides a first camera image, the first camera having a first sensor with a first plurality of sensor pixels covered at least in part with a non-standard color filter array (CFA) used to increase a specific color sampling rate relative to a same color sampling rate in a standard CFA, wherein the non-standard CFA includes a repetition of a $n \times n$ micro-cell where $n=6$ and wherein each micro-cell includes a color filter order selected from the group consisting of RBBRRB-RWRBWB-BBRBRR-RRBRBB-BWBRWR-BRRBBR, BBGRRG-RGRBGB-GBRGRB-RRGBBG-BGBRGR-GRBGBR, RBBRRB-RGRBGB-BBRBRR-RRBRBB-BGBRGR-BRRBBR and RBBRRB-BGBRGR-RBRBRB-BRBRBR-RGRBGB-BRBRBR;
- b) a second camera that provides a second camera image, the second camera having a second sensor with a second plurality of sensor pixels, the second plurality of sensor pixels being either Clear or covered with a standard CFA, wherein the second camera image has an overlap area with the first camera image; and
- c) a processor configured to process the first and second camera images into a fused output image, wherein in

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the overlap area pixels of the second camera image are registered with corresponding pixels of the first camera image.]

[3. The multi-aperture imaging system of claim 1, wherein the first camera is a Wide camera with a field of view FOV_w and wherein the second camera is a Tele camera with a field of view FOV_T smaller than FOV_w .]

[4. A method of acquiring images by a multi-aperture imaging system, the method comprising:

- a) providing a first image generated by a first camera of the imaging system, the first camera having a first field of view (FOV_1);
- b) providing a second image generated by a second camera of the imaging system, the second camera having a second field of view (FOV_2) such that $FOV_2 < FOV_1$, the second image having an overlap area with the first image; and
- c) fusing the first and second images into a fused image, wherein the fusing includes applying a registration process between the first and second images, the registration process including:
 - i. extracting a first Luma image from the first image
 - ii. extracting a second Luma image from the second image,
 - iii. applying low-pass filtering on the second Luma image in order to match its spatial frequency content to that of the first Luma image and to generate a low-pass second Luma image, and
 - iv. applying registration on the low-pass second Luma image and the first Luma image,

wherein the non-standard CFA includes a repetition of a $n \times n$ micro-cell where $n=4$ and wherein each micro-cell includes a BBRR-RBBR-RRBB-BRRB color filter order.]

[5. The method of claim 4, wherein $n=6$ instead of $n=4$ and wherein instead of each micro-cell including a BBRR-RBBR-RRBB-BRRB color filter order, each micro-cell includes a color filter order selected from the group consisting of RBBRRB-RWRBWB-BBRBRR-RRBRBB-BWBRWR-BRRBBR, BBGRRG-RGRBGB-GBRGRB-RRGBBG-BGBRGR-GRBGBR, RBBRRB-RGRBGB-BBRBRR-RRBRBB-BGBRGR-BRRBBR and RBBRRB-BGBRGR-RBRBRB-BRBRBR-RGRBGB-BRBRBR.]

6. A multi-aperture imaging system, comprising:

- a) a first camera that provides a first image, the first camera having a fixed first field of view ($FOV1$) and a first sensor with a first plurality of sensor pixels covered at least in part with a first color filter array (CFA);
- b) a second camera that provides a second image, the second camera having a fixed second field of view ($FOV2$) such that $FOV2 < FOV1$ and a second sensor with a second plurality of sensor pixels, the second image having an overlap area with the first image, the first sensor having a sensor overlap area with the second sensor and a sensor non-overlap area; and
- c) a third camera that provides a third image, the third camera having a fixed third field of view ($FOV3$) such that $FOV3 < FOV2$, and a third sensor with a third plurality of sensor pixels, the third image having an overlap area with the second image; and
- d) a processor configured to provide an output image based on a zoom factor (ZF) input that defines a respective field of view ($FOVZF$), such that for $FOV2 < FOVZF < FOV1$ the processor is further configured to select the first image as a primary image, to register the overlap area of the second image to the first

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image to obtain a fused image, and to provide the fused image as the output image from the point of view of the first camera,

wherein a CFA pattern of the first CFA in the sensor overlap area differs from a CFA pattern of the first CFA in the sensor non-overlap area, and wherein a demosaicing process applied to the first CFA in the sensor overlap area differs from a demosaicing process applied to the CFA pattern of the first CFA in the sensor non-overlap area.

7. The multi-aperture imaging system of claim 6, wherein if $FOV3 > FOVZF$, then the processor is further configured to provide an output image from the point of view of the third camera.

8. A multi-aperture imaging system, comprising:

a) a first camera that provides a first image, the first camera having a fixed first field of view (FOV1) and a first sensor with a first plurality of sensor pixels covered at least in part with a first color filter array (CFA);

b) a second camera that provides a second image, the second camera having a fixed second field of view (FOV2) such that $FOV2 < FOV1$ and a second sensor with a second plurality of sensor pixels, the second image having an overlap area with the first image, the first sensor having a sensor overlap area with the second sensor and a sensor non-overlap area; and

c) a third camera that provides a third image, the third camera having a fixed third field of view (FOV3) such that $FOV3 < FOV2$, and a third sensor with a third plurality of sensor pixels, the third image having an overlap area with the second image; and

d) a processor configured to provide an output image based on a zoom factor (ZF) input that defines a respective field of view (FOVZF), such that for $FOV3 < FOVZF < FOV2$ the processor is further configured to select the second image as a primary image, to register the overlap area of the third image to the second image to obtain a fused image, and to provide the fused image as the output image from the point of view of the second camera,

wherein a CFA pattern of the first CFA in the sensor overlap area differs from a CFA pattern of the first CFA in the sensor non-overlap area, and wherein a demosaicing process applied to the first CFA in the sensor overlap area differs from a demosaicing process applied to the CFA pattern of the first CFA in the sensor non-overlap area.

9. The multi-aperture imaging system of claim 8, wherein if $FOV3 > FOVZF$, then the processor is further configured to provide the output image from the point of view of the third camera.

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10. A method of acquiring images by a multi-aperture imaging system, comprising:

a) providing a first image generated by a first camera of the imaging system, the first camera having a fixed first field of view (FOV1) and a first sensor with a first plurality of sensor pixels covered at least in part with a first color filter array (CFA);

b) providing a second image generated by a second camera of the imaging system, the second camera having a fixed second field of view (FOV2) such that $FOV2 < FOV1$, and a second sensor with a second plurality of sensor pixels, the second image having an overlap area with the first image, the first sensor having a sensor overlap area with the second sensor and a sensor non-overlap area;

c) providing a third image generated by a third camera of the imaging system, the third camera having a fixed third field of view (FOV3) such that $FOV3 < FOV2$, and a third sensor with a third plurality of sensor pixels, the third image having an overlap area with the second image; and

d) using a processor to provide an output image from a point of view of the first camera, the second camera, or the third camera, based on a zoom factor (ZF) input that defines a respective field of view (FOVZF) such that:

if $FOV2 < FOVZF < FOV1$, then the processor is configured to select the first image as a primary image, to register the overlap area of the second image to the first image to obtain a fused image and to provide the fused image as the output image from the point of view of the first camera,

if $FOV3 < FOVZF < FOV2$, then the processor is configured to select the second image as a primary image, to register the overlap area of the third image to the second image to obtain a fused image and to provide the fused image as the output image from the point of view of the second camera, and

if $FOV3 > FOVZF$, then the processor is configured to provide an output image from the point of view of the third camera,

wherein a CFA pattern of the first CFA in the sensor overlap area differs from a CFA pattern of the first CFA in the sensor non-overlap area, and wherein a demosaicing process applied to the first CFA in the sensor overlap area differs from a demosaicing process applied to the CFA pattern of the first CFA in the sensor non-overlap area.

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