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Review

A review of micromirror arrays

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ABSTRACT

The aim of this paper is to provide a review of micromirror array (MMA) technologies (2631 MMA research papers and patents were reviewed for this effort). The performance capabilities of 277 MMA designs from 49 companies and 23 academic research groups are categorized and compared. The designs are categorized according to *(i)* their array's dimension (e.g., 2D arrays consisting of mirrors that cover a surface, 1D arrays consisting of mirrors in a row, and 0D arrays consisting of only a single mirror), *(ii)* the nature of the surface of their mirrors (e.g., continuous or discrete), *(iii)* what combination of tip, tilt, and/or piston degrees of freedom (DOFs) they achieve, and *(iv)* how they are actuated. Standardized performance metrics that can be systematically applied to every MMA design (e.g., mirror area, fill factor, pitch, range of motion, maximum acceleration, actuator energy density, and number of uncontrolled DOFs) are defined and plotted for existing designs to enable their fair comparison. Theoretical bounds on what is physically possible for MMAs to achieve are also derived and depicted in these plots to highlight the amount of performance improvement that remains to be achieved by future designs and guidelines are provided to aid in the development of these future designs.

1. Introduction

Micromirror arrays (MMAs) consist of a periodic pattern of closely packed small mirrors (i.e., millimeter-sized or smaller), which can be actuated to steer or manipulate the phase of light. Typically, the mirrors that constitute such arrays can be controlled to achieve various combinations of tip, tilt, and/or piston degrees of freedom (DOFs) to manipulate the light that reflects off the array's surface. In the past 30 years, the rapid development of the microelectromechanical-systems (MEMS) field has given rise to hundreds of MMA designs, which have been utilized in optics [1], telecommunications [2], astronomy [3], biology [4], additive fabrication [5], and other advanced applications. A comprehensive review of such MMA designs, a comparison of their performance capabilities, and a knowledge of how closely these performance capabilities approach their theoretical performance limits would help *(i)* increase general awareness of MMAs and consequently increase their use in a variety of developing technologies, *(ii)* act as a guide for directing engineers in selecting or adapting the most appropriate MMA designs that best achieve a desired set of design requirements, and *(iii)* inspire and guide future engineers to create new MMA designs that more closely achieve the theoretical performance limits.

The overarching aim of this paper is thus to provide such a review of existing MMA technologies for achieving these objectives. Specifically, this review provides *(i)* a comprehensive database of existing MMA designs and their capabilities, *(ii)* an organized way to classify these designs into useful categories, *(iii)* standardized definitions of performance metrics that can be used to fairly compare the capabilities of MMA designs, *(iv)* key examples of high-performing MMA designs, *(v)* performance plots that facilitate rapid MMA design comparisons, and *(vi)* theoretical physical bounds on the performance capabilities of different types of MMA technologies.

To the best of our knowledge, all relevant MMA-related publications prior to 2017 including research papers and patents have been reviewed for this effort (i.e., 2631 publications in total). *The **scope of this paper**, however, is limited to MMA designs of any dimensionality (i.e., 2D arrays consisting of mirrors that cover a surface, 1D arrays consisting of mirrors in a single row, and 0D arrays consisting of only a single mirror) that have been (i) developed by industry (whether the company is still in business or not), and (ii) designed by any academic research group that has designed at least one 2D array of micromirrors that achieve tip, tilt, and piston DOFs or tip and tilt DOFs only.* The MMA-related publications generated by research groups that did not design any 2D arrays or did design 2D arrays but that achieve a tip only DOF, a piston only DOF, or tip and piston only DOFs were excluded from the scope of this paper since an unreasonably large number of such publications exist (i.e., many thousands, which is too large to reference). Moreover, the vast majority of such publications pertain to applications of general MMAs only or they pertain to the same simplistic tip-only design (i.e., a mirror

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Table 1
A summary of the database of categorized MMA designs adapted to enable readers to quickly identify designs within the performance plots provided in Section 5.

Design Number	Research Groups	References	Array Dimension	Surface	DOF	Actuation
1	Flexible Research Group and Lawrence Livermore National Laboratory	[27,28,66,67]	2	Discrete	TTP	Analog Comb
2	Boston Micromachines	[21,57]	2	Discrete	TTP	Analog Plate
3	Texas Instruments	[12,77–81]	2	Discrete	T	Digital Plate
4	Texas Instruments	[12,77–81]	2	Discrete	T	Digital Plate
5	Texas Instruments	[82]	0	Discrete	TT	Analog Lorentz
6	Lemoptix	[83]	0	Discrete	T	Resonant Lorentz
7	Lemoptix	[83]	0	Discrete	T	Analog[a] Lorentz
8	Lemoptix	[83]	0	Discrete	T	Resonant Lorentz
9	Lemoptix	[83]	0	Discrete	T	Analog[a] Lorentz
10	Lemoptix	[83]	0	Discrete	T	Resonant Lorentz
11	Lemoptix	[83]	0	Discrete	T	Analog[a] Lorentz
12	Lemoptix	[83]	0	Discrete	T	Resonant Lorentz
13	Lemoptix	[83]	0	Discrete	T	Analog[a] Lorentz
14	Lemoptix	[83]	0	Discrete	T	Resonant Lorentz
15	Lemoptix	[83]	0	Discrete	T	Analog[a] Lorentz
16	Lemoptix	[83]	0	Discrete	T	Resonant Lorentz
17	Lemoptix	[83]	0	Discrete	T	Analog[a] Lorentz
18	Lemoptix	[84]	0	Discrete	T	Analog Lorentz
19	Lemoptix	[84]	0	Discrete	T	Analog Lorentz
20	Lemoptix	[85]	0	Discrete	T	Resonant Thermal
21	Lemoptix	[85]	0	Discrete	T	Analog[a] Thermal
22	Lemoptix	[85]	0	Discrete	T	Resonant Lorentz
23	Lemoptix	[85]	0	Discrete	T	Analog[a] Lorentz
24	Lemoptix	[85]	0	Discrete	T	Resonant Lorentz
25	Lemoptix	[85]	0	Discrete	T	Analog[a] Lorentz
26	Lemoptix	[83–86]	0	Discrete	TT	Analog[a] Lorentz
27	Lemoptix	[83–86]	0	Discrete	TT	Analog[a] Lorentz
28	Lemoptix	[83–86]	0	Discrete	TT	Analog[a] Lorentz
29	Lemoptix	[83–86]	0	Discrete	TT	Analog[a] Lorentz
30	Lemoptix	[83–86]	0	Discrete	TT	Analog[a] Lorentz
31	Lemoptix	[83–86]	0	Discrete	TT	Analog[a] Lorentz
32	Adriatic Research	[87,88]	0	Discrete	TT	Analog[a] Comb
33	Adriatic Research	[87,88]	0	Discrete	TT	Resonant Comb
34	Adriatic Research	[88,89]	0	Discrete	TT	Analog[a] Comb
35	Adriatic Research	[88,89]	0	Discrete	TT	Resonant Comb
36	Adriatic Research	[88,90]	0	Discrete	TT	Analog[a] Comb
37	Adriatic Research	[88,90]	0	Discrete	TT	Resonant Comb
38	Adriatic Research	[91]	2	Discrete	TTP	Analog Comb
39	Adriatic Research	[92–94]	0	Discrete	TT	Analog Comb
40	Adriatic Research	[30,95]	0	Discrete	TTP	Analog Comb
41	Adriatic Research	[30,95]	2	Discrete	TTP	Analog Comb
42	Adriatic Research	[30,95]	2	Discrete	TTP	Analog Comb
43	Adriatic Research	[30,95]	2	Discrete	TTP	Analog Comb
44	Adriatic Research	[30,95]	2	Discrete	TTP	Analog Comb
45	Adriatic Research	[92,93,96]	0	Discrete	TT	Analog Comb
46	Adriatic Research	[97]	0	Discrete	TT	Resonant Comb
47	Adriatic Research	[97]	0	Discrete	TT	Analog[a] Comb
48	Adriatic Research	[98,99]	0	Discrete	T	Analog Comb
49	Adriatic Research	[98,99]	0	Discrete	TT	Analog Comb
50	Adriatic Research	[100,101]	0	Discrete	TT	Analog Comb
51	Adriatic Research	[100,101]	0	Discrete	TT	Analog Comb
52	Adriatic Research	[101–104]	0	Discrete	TP	Analog Comb
53	Adriatic Research	[105,106]	0	Discrete	TTP	Analog Comb
54	Adriatic Research	[107,108]	0	Discrete	T	Analog Comb
55	Adriatic Research	[109]	0	Discrete	T	Analog Comb
56	Adriatic Research	[108,109]	0	Discrete	T	Resonant Comb
57	IMEC	[7,110–117]	2	Discrete	T	Analog Plate
58	Fraunhofer IPMS	[118–128]	2	Discrete	T	Analog Plate
59	Fraunhofer IPMS	[118,123,129–135]	2	Discrete	T	Analog Plate
60	Fraunhofer IPMS	[136,137]	2	Discrete	T	Analog Plate
61	Fraunhofer IPMS	[138,139]	2	Discrete	T	Analog Plate
62	Fraunhofer IPMS	[140–143]	0	Discrete	T	Resonant Comb
63	Fraunhofer IPMS	[140–143]	0	Discrete	T	Analog[a] Comb
64	Fraunhofer IPMS	[140–143]	0	Discrete	TT	Resonant Comb

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