Supplementary Information

Microscopic artificial cilia - a review†

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Table S1: Fabrication methods along with materials used to fabricate artificial cilia and their sizes and other details reported in different studies are categorized here as per the flow chart shown in Fig. 5 of the main article. The type of motion named; rotation, back and forth of cilia is an approximation to tilted conical motion and 2D asymmetric motion respectively. Each section in the table is sorted as per the cilia sizes - smallest to largest.

Fabrication method	**Ref.**	**Material**	**Size*** □:l×w×t μm ◯:l×d μm	**Application**	**Actuation/ Sensing method**	**Type of motion**
Template based (MEMS)	[1]	PDMS, CrO2	47×5.7	localized actuation	magnetic/ optic	-
	[2]	Cobalt NW	50×0.07	flow/vibration	magnetic	-
	[3]	hydrogel	50×1-10	flow generation	pH/magnetic/ electric	rotation
	[4]	PDMS, CIP	46-68.8×8.5-9.1	droplet manipulation	magnetic	back and forth
	[5]	PEG	170×50	acoustic sensing	piezoelectric	-
	[6]	PDMS, CIP	350×50	fluid pumping	magnetic	tilted conical
	[7]	SU-8, Hydrogel	400-800×50	flow sensing	piezoelectric	-
	[8]	PDMS	1000×100	flow generation	ballchain wave excitation	wave-like
	[9]	PDMS, iron	2000×400×100	flow generation	magnetic	metachrony
Template based 3D printing	[10]	Ecoflex, NdFeB	4000×800	flow	magnetic transport	metachrony
	[11]	PDMS	4000×1500	air/water flow sensor	-	-
Template free (MEMS)	[12]	PDMAA MABP	70×20×0.9	flow generation	magnetic	2D asymmetric
	[13]	Chromium, polymer	100×20×1.02	mixing	electrostatic	2D asymmetric
	[14]	Ni-Fe	150×20×0.7	flow generation	magnetic	metachrony
	[15]	PDMS Fe-C	300×100×15	fluid manipulation	magnetic	2D asymmetric
	[16]	Ni-Fe permalloy	480×10×0.055	fluid/particle manipulation	magnetic	2D asymmetric
	[17]	Au/PPy	500×50×0.11	mixing	electrochemical	channel compression
	[18]	SU-8	600×800	flow sensing	piezoresistive	-
	[19]	Co,Ni, galfenol NW	4000×1500	sensor	magnetic	-
	[20]	IPMC	1200×5000×370	flow sensing	ionic polymer	-
Template free 3D/4D printing	[21]	fiber PVDF Al	$L/d = 500$	flow sensing	piezorelectric	-
	[22]	PU/CIP	3000×200	flow generation	magnetic	metacrony
	[23]	PU/CIP	3000×240	transport	magnetic	metachrony, worm-like
	[24]	Sr-ferrite liquid crystal	10000×3000×10	actuator	optics	2D asymmetric
Cilia pulling	[25]	PDMS, CIP	250×-	fluid pumping	magnetic	tilted conical
	[26]	PET,PU,PS, PMMA,PVP	100000×100	humidity sensing	optics	-
Needle punching	[27]	PDMS Co powder	2500×9-700	transport	magnetic	back and forth
	[28]	metal-metaklett	2500×2500×200	flow generation	acoustic	-
	[29]	PDMS-NdFeB	2800×130	mixing	magnetic	rotation
	[30]	PDMS-BaTiO3	3500×9-700	tranport	magnetic	back and forth
PCTE molds	[31]	Maghemite, PDMS	25×0.2-1	microfluidics	magnetic	tilted conical
	[32]	Maghemite, PDMS	10-25×0.2-0.8	flow/ mixing	magnetic	tilted conical
	[33]	Magnetite composite	6-47×0.4-3	microfluidics/ robotics	magnetic	rotation
	[34]	Nickel, PDMS	-×2	blood clot stiffness	magnetic	-

Size* □ = flap like cilia, ◯ =cylindrical/conical cilia, l:length, w:width, t:thickness, d:diameter

Table S1 continued:

Fabrication method	Ref.	Material	Size* □:l×b×t μm ◯:l×d μm	Application	Actuation/ Sensing method	Type of motion
Micromachinig	[35]	PDMS-NdFeB	300×50	mixing	magnetic	rotation
	[36]	PDMS-NdFeB	300×50	flow generation	magnetic	rotation
	[37]	PDMS-NdFeB	400×50	pumping/ mixing	magnetic	rotation
	[38]	polyethylene, NW	-×50	vibration sensor	magnetic	-
	[39]	PDMS, CIP	690×86	actuation	magnetic	metachrony
	[40]	PDMS-NdFeB	800×50	flow generation	pneumatic	rotation
	[41]	PDMS, Fe NW	1000×200	tactile sensors	magnetic	-
	[42]	PMMA, PC	2000×300	flow sensing	piezoresistive	-
	[43]	PDMS-NdFeB	2500×250	mixing	magnetic	rotation
	[44]	Ecoflex-NdFeB	7000×-	robots	magnetic	2D asymmetric
	[45]	PDMS-	8000×1000	pumping	air pressure	metachrony
	[46]	polyethylene NW	6000-16000×1000	flow generation	pneumatic	2D asymmetric
Part assembly	[47]	PMMA	2000×300	flow sensor	electroactive polymer	-
	[48]	PMMA	5000×500	flow sensor	piezoelectric	-
	[49]	Au	13000×320	actuation	electric	back and forth
	[50]	Cu	10000-20000×230	flow generation	thermal	metachrony
	[51]	Plyethelene, Au	16000-20000×10	flow generation	electric	metachrony
	[52]	IPMC	35000×2000×500	flow generation/ sensors	electroactive polymer	rotation
	[53]	Au-IPMC, PC nafion	38000×400×175	sensor	electroactive polymer	-
Self assembly	[54]	PPy NW, CoFe	1×0.133-0.309	sensor	magnetic	-
	[55]	paramagnetic colloids	6×3	actuation	magnetic	rotation
	[56]	ZnO nano sheets	-	photocatalytic reaction	magnetic	rotation
	[57]	PAmPh Co nano-magnetic beads	20×0.2	flow generation/ pH sensing	magnetic	rotation
	[58]	Ecoflex-NdFeB Co	20×0.2	particle transport	magnetic	rotation
	[59]	PBA magnetic beads	20×3	flow generation	magnetic	tilted conical
	[60]	superparamagnetic spheres	30.8×1	flow generation	magnetic	tilted conical
	[61]	superparamagnetic beads	38.8-40×-	pumping	magnetic	tilted conical
	[62]	superparamagnetic beads	45×50	flow generation	magnetic	tilted conical
	[63]	PAmPh, Co nano-magnetic beads	10-100×0.4-0.8	mixing	photothermal	rotation
	[64]	polystyrene Co nanoparticles	40-200×-	flow pumping	magnetic	-
	[65]	poly acrylic colloidal particles	50-300×-	pumping	magnetic	rotation
	[66]	Carbon NW	500×-	flow	electro-osmosis	back and forth
	[67]	PDMS Co	600×34	mixing	photothermal	rotation
	[68]	PDMS, Co powder	920×40	mixing	magnetic	-
	[69]	PDMS Co	500-1000×20-80	sensing	magnetic, pressure	-
	[70]	PDMS, Co powder	1340-1730×-	mixing	magnetic	back and forth
	[71]	PDMS, Co powder	1340-1730×-	photocatalytic reaction	magnetic	-
	[72]	polyurethane, CIP	250-2000×-	flow generation	photothermal	back and forth
	[73]	PDMS Co	500-2500×100-300	sensing	magnetic	-
	[74]	PS-CoNP	3000×250	-	magnetic	-
	[75]	polystyrene, Co	1000-6000×-	mixing	magnetic	back and forth
	[76]	polystyrene Co nano particles	15000-5000×0.235	acuation	magnetic	back and forth

Size* □ = flap like cilia, ◯ =cylindrical/conical cilia, l:length, b:width, t:thickness, d:diameter

Table S2: Comparison of particle and droplet manipulation methods using artificial cilia, published in the recent literature.

Ref.	Cilia Type	Cilia Geometry □ : l×w × t[μm^3] ◯ : l×d[μm^2]	Cilia Motion	Particle/ Type	Particle/ Droplet Size (μm/ μL)	Particle/ Manipulation	Maximum Transport Speed ($\mu m/s$)
[77]	cylindrical magnetic artificial cilia	40×5	bending	water droplet, silicon carbride	60 50	transportation, capture and release	200 320
[78]	rectangular magnetic artificial cilia	46×17	bending	water droplet	10 μL	forward and backward transportation	-
[79]	mushroom-like magnetic pillar array	$(127 \pm 28)\times(27\pm8)$, $(139 \pm 32) \times (42 \pm 14)$	bending and oil droplets	water droplet,	13 μL	transportation on a inclined surface, capture and release	-
[80]	cylindrical magnetic artificial cilia	350 × 50	3D conical motion	micro algae	12	removal	-
[81]	cylindrical magnetic artificial cilia	350 × 50	3D conical motion	PLA particles in water, sand grains	$30 - 500$ $500 - 2000$	removal	-
[82]	cylindrical magnetic artificial cilia	350 × 50	3D tilted conical motion	PLA particles in water	$400 - 800$	multi-directional transportation	800
[83]	conical magnetic artificial cilia	$(800 - 1200)$ × $(60 - 100)$	bending	water droplet	10 μL	omnidirectional controllable water delivery	-
[84]	magnetic flap-shaped	940 × 2390 × 93	metachronal motion	water droplets, liquid metal in water	$2 - 10$ μL	horizontal and vertical transportation, capture and release, mixing	5860
[85]	cylindrical magnetic artificial cilia	1014 × $(125 - 205)$	metachronal motion	water droplet	1-6 μL	unidirectional transportation on specific orbit	-
[86]	magnetic pillar array	1300 × 130	-	water droplet, ice particles	10 μL	multidirectional transportation	-
[87]	conical magnetic artificial cilia	L=3000	metachroanl motion	PS particles	2500	horizontal transportation	900
[88]	conical magnetic artificial cilia	3500 × 2	metachroanl motion	SiO_2in water	2500	horizontal transportation	73
[89]	conical magnetic artificial cilia	L=$2500 - 4000$	metachronal motion	water droplet, oil droplet in water	$2100 - 4200$	transportation on horizontal and inclined surfaces	28300 31500

Size* □ = flap like cilia, ◯ =cylindrical/conical cilia, l:length, b:width, t:thickness, d:diameter

Table S3: The applications in which cilia structures are used to sense flow in a liquid/ gaseous medium are sorted by its size in the interest of finding relevant methods of sensing in microfluidics. The flow velocity, the level of vibrations in liquid/ air (Hydrophones) and the acceleration of fluids (accelerometer) the cilia based sensors can measure are also presented.

Sensing principle	**Ref.**	**Material**	**Size*** □:l×w×t μm ◯:l×d μm	**Medium**	**Flow velocity**	**Flow measurement resolution**
Piezoresistive	90	permalloy	820×0-10×100	water	1 m/s	-
	91	-	800×400×250	air	10s of cm/s to 2m/s	-
	18	Si+SU8	700×-	air/water	-	< 1 m/s
	92	AlN_3 + Mo	(200-600)×100×0.7	water	0.3 bar	0.025 bar
	93	red wax	1000×100×40	water	-	184.2 dB
	94	permalloy, Cr/Au, Al	(600-1500)×10×200	air	0-30 m/s	-
	42	PMMA	2000×300	nanoindentor	-	-
	47	PMMA	2000×300	water	0-100 L/min	-
	95	PMMA+PC	2000×300	water	-	-
	96,97	PU	3000×500	-	-	-
	98	$Si + SiO_2$	(1500-3500)×130×20	water (hyrophone)	20 Hz - 3 kHz	-(182-192) dB
	99	glass fibre +CNT	(750-4000)×(25-36)	air	12 m/s	-
	11	graphene +PDMS	4000×1500	air	90 m/s	-
	100	plastic	5000×150	water (hyrophone)	20 Hz - 2 kHz	-165 dB
	101	photosensitive resin	5000×175	water	0-200Hz	2.73×10^{-2} Vms^2/kg
	102	optical fibre	5000×200	water (accelerometer)	-	x=0.755 mV/g, y=0.683 mV/g
	103	Si	5000×200	air (accelerometer)	0-1000 Hz	x=0.755 mV/g, y=0.683 mV/g
	104	optical fibre	(3500-5000)× (100-120)×20	water (hyrophone)	-	-185 dB
	105	Si	7000×200	water	0-1 Hz	0.7552 mV/g
	106	Si	8000×400	water	0.6	0.05m/s
	107	Cu	8000×2000×100	water	0.45 m/s	0.05 m/s
	108	Cu	8000×2000×100	water	0.45 m/s	0.05 m/s
	109	PDMS, GNP ink	(10000-20000)×3000	air/ water	0-9 m/s -	- 16-30μm/s
	110	-	20600×3000	air/water	0-500 m/s	4.93 mm/s
Piezoelectric	111	PVDF	-×25	air	-	-
	7	SU-8, hydrogel	400-800×50	water	-	-
	112	CNT	4000×350	air/water	-	5 mm/s
	113	VACNT	-	water	-	5 mm/s
	48	PMMA	-	water	-	0.23 mm/s
	114	CNT+Pt	1500×260	air	-	5 mm/s
	115	$BaTiO_3$ plastic	4000×350	water	20 Hz - 2 kHz	-189.3 dB
Capacitive	116	SU-8	500×50	air	0.6 m/s	-
	117	SU-8	900×50	air	-	-
	118	SU-8	1000×-	air	0.1-1 m/s	-
	119	-	1900×220	air	0-15 m/s	2 cm/s
	120	ecoflex, liquid metal	5000×5000×175	water	0.06 m/s	-
	121	hydrogels	18000×260×100	-	-	-

Size* □ = flap like cilia, ◯ =cylindrical/conical cilia, l:length, w:width, t:thickness, d:diameter

Table S3 continued:

Sensing principle	**Ref.**	**Material**	**Size*** □:l×w×t μm ◯:l×d μm	**Medium**	**Flow velocity**	**Flow measurement resolution**
Magnetic	[122]	Fe-Ga NW	-×0.001-0.1	air	300 Hz - 5 kHz	-
	[54]	PPy NW	1×0.08-0.2	air	-	-
	[123]	Fe-Ga NW	5×0.1	air	-	-
	[2]	Co NW	50×0.7	water, Air	6 mL/min 1-5Hz	136 μL/min
	[124,125]	Fe-Ga NW	25-100×0.02-0.2	Liquids	400 Hz - 10 kHz	-
	[126,127]	Fe NW, PDMS/SU-8	500×100, 20×5	water	7.8 mm/s	0.56 mm/s
	[74]	PS-CoNP	3000×250	-	-	-
Other types						
FSR	[96,97]	polyurethane	3000×500×100	-	-	245 ppm/μm
	[47]	PMMA	2000×300, 20×5	water	0-100 L/min	
	[42]	PMMA	2000×300, 20×5	water	0-100 L/min	
IMPS	[20]	nafion	500×1200×370	-	-	-
Resonance	[128]	polymer	9000×1000	air	43.27 and 41.85 mm/s	-
	[129]	ABS hollow post	8000×800	air	-	-

Size* □ = flap like cilia, ◯ =cylindrical/conical cilia, l:length, b:width, t:thickness, d:diameter

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