# GECKO-INSPIRED, CONTROLLED ADHESION AND ITS APPLICATIONS

### **Thesis Committee**

Professor Metin Sitti, Chair Professor John A. Rogers Professor Nadine Aubry Professor Maarten de Boer

> Yiğit Mengüç January 19th, 2012

© Copyright by Yiğit Mengüç 2012 All Rights Reserved

## Abstract

Gecko feet stick to almost anything, in almost any condition (including underwater and in space), but do not stick unintentionally, do not stick to dirt, and enable the gecko to literally run up the walls. When climbing a smooth surface, geckos can attach and detach each foot very quickly (detaching a foot takes 15 milliseconds) and with almost no noticeable force, but if attached perfectly they could theoretically hold tens of times their body weight. In contrast to gecko adhesion, conventional adhesives, made of soft tacky materials, tend to leave residues, pick up dirt easily, stick to themselves strongly and are useless underwater. Gecko feet rely on completely different principles, utilizing arrays of tiny mechanical structures made of very stiff protein which react to pressing and dragging with some very smart behavior. This thesis work is primarily concerned with taking inspiration from the principles of gecko-adhesion in order to control the attachment of synthetic structured adhesives.

We present gecko-inspired angled elastomer micropillars with flat or round tip endings as compliant pick-and-place micromanipulators. The pillars are 35  $\mu$ m in diameter, 90  $\mu$ m tall, and angled at an inclination of 20°. By gently pressing the tip of a pillar to a part, the pillar adheres to it through intermolecular forces. Next, by retracting quickly, the part is picked from a given donor substrate. During transferring, the adhesion between the pillar and the part is high enough to withstand disturbances due to external forces or the weight of the part. During release of the part onto a receiver substrate, the contact area of the pillar to the part is drastically reduced by controlled vertical or shear displacement, which results in reduced adhesive forces. The maximum repeatable ratio of pick-to-release adhesive forces was measured as 39 to 1. We find that a flat tip shape and shear displacement control provide a higher pick-to-release adhesion ratio than a round tip and vertical displacement control, respectively. We present a model of forces to serve as a framework for the operation of this micromanipulator. Finally, demonstrations of pick-and-place manipulation of  $\mu$ m-scale silicon microplatelets and a cm-scale glass cover slip serve as proofs of concept. The compliant polymer micropillars are safe for use with fragile parts, and, due to exploiting intermolecular forces, could be effective on most materials and in air, vacuum, and liquid environments.

We present a study of the self-cleaning and contamination resistance phenomena of synthetic gecko-inspired adhesives made from elastomeric polyurethane. The phenomenon of self-cleaning makes the adhesive foot of the gecko robust against dirt, and makes it effectively sticky throughout the lifetime of the material (within the molting cycles). So far synthetic gecko adhesives fail to capture this behavior and self-cleaning remains the least studied characteristic in the field geckoinspired adhesives. In this work we use two distinct arrays of micropillars with mushroom-shaped tips made from polyurethane. The two geometries we use all have the same aspect ratios of pillar height to base diameter of about 2 to 1, and all have mushroom tips that are twice the diameter of base. The pillar tip diameters are 20  $\mu$ m and 95  $\mu$ m, and we will refer to them as the small and large pillars, respectively. We contaminate the adhesives with simulated dirt particles in the form of well-characterized soda lime glass spheres ranging in diameter from 1 to 250 µm. Both micropillar arrays recovered adhesive strength after contamination and cleaning through dry, shearing contact with glass. In a best case scenario, we found that large pillars contaminated with 150-250 µm diameter particles can rid the tips of contaminating particles completely and recover 90% of the initial adhesive strength. This finding is significant because it is the first demonstration of adhesion recovery through dry self-cleaning by contact to a non-sticky cleaning substrate. The degree to which adhesion is recovered is superior to any conventional adhesive and is nearly identical to the gecko itself.

This thesis presents a study of controlling adhesion in gecko-inspired adhesives. This control is achieved by maximizing or minimizing attachment strength on demand by simple mechanical loading, and enables robotic manipulation tasks and the recovery of adhesion after contamination. Looking forward, we can predict what is possible for gecko-inspired adhesives if the discoveries in this thesis are implemented, and if other shortcomings in the field are resolved. Looking at the applications already under development, it seems clear that medical adhesives have great potential, and climbing robots might achieve significant utility. In consumer products, gecko-adhesives might replace Velcro®and zippers in clothing, and might become a critical component in sports gear, e.g. soccer goal keeper and rock climber gloves. The reversible, controllable nature of the adhesion, as well as its incredible bonding strength, suggests more impressive possibilities for gecko-inspired adhesives: perhaps it might act as a fastener for temporary or emergency construction. We might yet see rolls of single-sided and double-sided gecko-tape sold in hardware stores, not as a replacement for duct tape, but as a replacement for nails, staples and screws.

## Acknowledgments

This work is dedicated to my mother, father and sister. Their love and support has been the foundation upon which I continue to pursue my passion.

I would like to acknowledge the pivotal role that my advisor, Professor Metin Sitti, played in my development as a PhD candidate and as a person. He always pushed me to be the best researcher, scholar, and scientist I could be through his feedback and advice, and he always helped guide me towards the highest impact work and results possible. His mentorship has shaped me into the mechanical engineer that I am now, and all my future works will be rooted in the experience and wisdom that I gained under him. I would also like to graciously acknowledge the kind support and intellectual stimulation from the members of my thesis committee, Professor Nadine Aubry, Professor Maarten de Boer, and Professor John A. Rogers, who all helped inspire me through their scientific vision and technical inquiries.

Finally, there are so many people who have given me so much help over the last four years. I can not adequately express my gratitude here, but I want them to be directly associated with this work, so their names are listed here in no particular order: Michael Röhrig, Eric Diller, Onur Özcan, Slava Arabagi, Mike Murphy, Burak Aksak, Shuhei Miyashita, Paul Glass, Eugene Cheung, Seok Kim, Uyiosa Abusomwan, Jiho Song, Sang Yoon Yang, Sehyuk Yim, Matt Woodward, Lindsey Hines, Steve Floyd, Chytra Pawashe, Çağdaş Onal, Alan McGaughey, Casey Kute, Phil LeDuc, Burak Özdoğanlar, Tony Kim, Carsen Kline, Chris Bowman, Jim Dillinger, Ed Wojciechowski and John Fulmer

Financial support was provided by the Boeing Company, the Claire and John Bertucci Fellowship, grants from the National Science Foundation (CMMI-1130520 and CMMI-0800408) and the Department of Mechanical Engineering at Carnegie Mellon.

# Contents

A	bstrac	et			iii
A	cknov	vledgme	ents		v
Li	ist of '	<b>Fables</b>			xi
Li	ist of l	Figures		Х	xvii
N	omen	clature		Х	xvii
1	Intr	oductio	n to Gecko-Inspired Adhesives		1
	1.1	Motiva	ation		1
	1.2	Biolog	gical Inspirations		4
		1.2.1	Key discoveries in gecko adhesion		5
		1.2.2	Structured adhesion in other animals		6
		1.2.3	Summary of observed principles of micro-structured adhesives .		6
	1.3	Mecha	anical Principles of Structured Adhesives		9
		1.3.1	Adhesion		9
			Contact splitting		9
		1.3.2	The importance of the terminal tip geometry		10
			Matting condition as a limiting principle		11
			Flaw insensitivity		12

			The effect of surface roughness	12
			Additional principles	13
		1.3.3	Friction	15
			Classic friction theory for smooth flat surfaces	15
			Theory and experimental results of structured interfaces in shear	16
	1.4	Gecko	-Inspired Adhesives and their Fabrication	17
		1.4.1	Macro- and Microscale Fibers	17
			Modifications leading to Adhesion Control	19
			Angled Fibers	20
			Tip Modifications	22
		1.4.2	Nanoscale Fibers	23
		1.4.3	Hierarchical Fibers	24
	1.5	Applic	cations of Bio-Inspired Adhesives	27
		1.5.1	Robotics	27
			Mobile Robots	27
			Manipulators	28
		1.5.2	Medical Devices	30
	1.6	Resear	rch Objectives	32
	1.7	Contri	butions	33
2	Gec	ko-Insp	ired, Controllable Adhesives Applied to Micromanipulation	34
	2.1	Introd	uction	34
	2.2	Experi	mental Methodology	37
		2.2.1	Fabrication	37
		2.2.2	Detailed Fabrication Methodology	39
		2.2.3	Experimental Setup	41
			Vertical Displacement Experiments	43
			Shear Displacement Experiments	43
			Demonstration of Pick-and-Place Manipulation	43
	2.3	Result	8	44
		2.3.1	Characterization of the curvature of the round tip structure	44

		2.3.2	Effect of tip shape	44
		2.3.3	Effect of shear displacement	50
		2.3.4	Effect of pull-off speed on adhesive force	50
		2.3.5	Adhesion dependence on preload	53
		2.3.6	Demonstration of manipulation	55
	2.4	Discus	sion	58
		2.4.1	Picking, holding and releasing models of manipulation	58
			Picking	58
			Holding	61
			Releasing	61
		2.4.2	Modeling the contact-area of a round tip pillar	62
		2.4.3	Simulation of stress distribution across the surface of the flat tip pillar	70
			Modeling and Simulation Results	71
	2.5	Conclu	usions	72
3	Con	tact Sel	f-Cleaning of Gecko-Inspired Adhesives	73
	3.1	Introdu	uction	73
	3.2	Materi	als and Methods	78
	3.3	Result	s and Discussion	80
	3.4	Conclu	isions	91
4	Con	clusion	5	92
	4.1	Contri	butions of this Work	94
		4.1.1	Adhesion Control of Angled Micropillars	94
			Preload Control	94
			Vertical and Shear Displacement Control	94
		4.1.2	Model of contact area of the fiber under compressive load	94
		4.1.3	Demonstration of Micropillar Arrays and Single Structures as	
			Novel Manipulators	95
			Developed new fabrication techniques to create arrays of structured	
			adhesives	95
			Micromanipulation	95

			Macromanipulation	95
		4.1.4	Contamination-Resistant and Self-Cleaning Adhesives	96
			Demonstrated Significant Adhesion Recovery Through Dry, Con-	
			tact Self-Cleaning	96
			Formulated Regimes of Self-Cleaning	96
	4.2	Future	Directions: Unsolved Challenges and Possible Applications	97
		4.2.1	Translate Micromanipulation Research Results into Industrial Ap-	
			plications	97
			Characterize Viscoelastic Behavior in the Micromanipulator	97
		4.2.2	Improved Characterization and Modeling of Contact Process of the	
			Micromanipulators	97
			Anisotropy in Micromanipulators	98
			Micromanipulation of Non-Rectilinear Parts in Parallel	99
			Automation of Micromanipulation	99
		4.2.3	Developing and Improving Self-Cleaning Adhesives	00
			Characterize Principles of Self Cleaning as it Relates to All	
			Regimes of Structured Adhesives	00
			Self-Cleaning of Real-World Contaminants	02
			Implement Hierarchical Structures to Act as Particle Traps 1	02
			Non-dimensional Parametric Analysis of Self-Cleaning 1	03
			Adhesion Recovery in Climbing Robots	03
A	Waa	lbot II:	Adhesion recovery and improved performance of a climbing robot	
	usin	g fibrill	ar adhesives 1	04
	A.1	Introdu	action $\ldots$ $\ldots$ $\ldots$ $\ldots$ $\ldots$ $1^{1}$	05
	A.2	Length	Scale Optimization	08
	A.3	Advan	cements for Semi-Autonomous Control	11
		A.3.1	Adhesion Recovery	12
			Adhesion Sensor Selection	12
			Adhesion Level Sensing and Recovery	14
		A.3.2	Motion Planning	16

	A.4 Conclusion	118
B	Interfacial Contact Patch Visualization through Interferometric Microscopy	121
С	Details of SU-8 Photolithography	123
Re	eferences	147

# List of Tables

2.1	Fiber Parameters																				•	•	•								•		6	64
-----	------------------	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	---	---	---	--	--	--	--	--	--	--	---	--	---	----

## List of Figures

1.1 (a) A series of images showing the ever smaller attachment structures of the gecko, from its foot down to the hair-like setae that cover the bottom of each toe, and the spatulae that terminate the tips of the setae. (Reprinted with permission [1]. Copyright 2006, Springer.) (b) One of the first SEM images of gecko setae taken in 1965 by Ruibal and Ernst (Reprinted with permission [2]. Copyright 1965, Wiley.) (c) An SEM image of the entire setal stalk clearly showing asymmetric morphology. (Reprinted with permission [3]. Copyright 2006, Company of Biologists.) (d) Hierarchical polymer microstructure with mushroom tip and backing layer noted. (Reprinted with permission [4]. Copyright 2009, American Chemical Society.) (e) Hierarchial polymer structure composed of angled nanopillars molded on top of vertical micropillars.(Reprinted with permission [5]. Copyright 2009, National Academy of Sciences.)

The seven principles of gecko adhesion as outlined by Autumn [6] are pre-1.2 sented here with representative observations from literature. (a) Evidence for van der Waals forces, as opposed to capillary forces, is shown by the equivalent attachment forces of a gecko foot to hydrophobic GaAs and hydrophilic SiO<sub>2</sub> surfaces. (Reprinted with permission [7]. Copyright 2002, National Academy of Sciences.) (b) High adhesion and friction forces are achieved for low preloads when the gecko foot is dragged in the direction of the curvature of the setae. (Reprinted with permission [8]. Copyright 2006, Company of Biologists.) (c) Easy detachment of the gecko foot is observed if it is dragged against the curvature of the setae. (Reprinted with permission [8]. Copyright 2006, Company of Biologists.) (d) The anisotropic attachment of the gecko foot is replicated in a patch of synthetic adhesive composed of angled pillars with angled mushroom tips. The inset images show microscopic deformations of the individual micropillars under directional loading. (Reprinted with permission [9]. Copyright 2009, Wiley.) (e) In their default, undeformed state, the gecko setal array is highly nonsticky, which is visually represented here by its superhydrophobic contact with a water droplet. (Reprinted with permission [1]. Copyright 2006, Springer.) (f) Gecko setae have evolved to be non-matting, but man-made synthetics need to be optimized, as can be seen here where the top image shows free standing micropillars, but in the bottom image the pillars are matted together. (Reprinted with permission [10]. Copyright 2011, Wiley.) (g) Even when a gecko's foot becomes completely saturated with dirt, after just a few simulated steps it can regain a large portion of the original attachment strength; these SEM images show the dirty and after cleaning states of a setal array. (Reprinted with permission [11]. Copyright 2005, National Academy of Sciences.)

- (a) Vertical nanopillars created by oxygen plasma etching of polyimide. 1.4 (Reprinted with permission [13]. Copyright 2003, Nature Publishing Group.) (b) Polymer micropillars formed by casting into a micromachined negative template. (Reprinted with permission [14]. Copyright 2007, the Royal Society.) (c) Wedge shaped polymer microstructures cast from a negative photolithography template. (Reprinted with permission [15]. Copyright 2009, the Royal Society.) (d) Polypropylene nanofibers molded and etched free from a commercially available polycarbonate filter. (Reprinted with permission [16]. Copyright 2006, American Physical Society.) (e) Micropillars with triangular cross-sections were cast from dry etched silicon wafers. (Reprinted with permission [17]. Copyright 2011, Wiley.) (f) Hierarchical nanopillars formed through capillary force assisted lithography. (Reprinted with permission [5]. Copyright 2009, National Academy of Sciences.) (g) Hierarchical micropillars produced through a single step casting of polymer to a multiple-level photolightography template. (Reprinted with permission [18]. Copyright 2009, Wiley.) (h) Micropillars with mushroom tips cast from a dry etched siliconon-insulator wafer template. (Reprinted with permission [19]. Copyright 2007, American Institute of Physics.) (i) Angled micropillars were formed from angled-light photolithography, and the angled mushroom tips were formed from a subsequent dipping into liquid polyurethane. (Reprinted with permission [9]. Copyright 2009, Wiley.) (j) Dipping micropillars into liquid polymer created the round tips in the left image, and subsequently pressing and shearing them against a clean substrate created the offset spatula tips in the right image. (Reprinted with permission [20]. Copyright 2007, Wiley) . . .

1.5	This figure is an outline of the four schemes for creating hierarchical gecko-
	inspired adhesives. Reproduced with permission. (Reprinted with permis-
	sion [21]. Copyright 2011, Wiley.)
1.6	(a) Waalbot [22] and (b) Stickybot [23] are two robots utilizing gecko-
	inspired adhesives to climb walls quietly and efficiently. (Waalbot -
	Reprinted with permission [22]. Copyright 2010, SAGE Publications.)
	(Stickybot - Reprinted with permission [23]. Copyright 2007, IEEE.) 28
1.7	(a) The top two images show the deformed state of the square cross-section
	micropillar in contact with a silicon microplatelet part, and the lower im-
	age shows an assembly created with the Kim et al. micromanipulator.
	(Reprinted with permission [24]. Copyright 2010, National Academy of
	Sciences.) (b) The image to the left shows an array of angled micropillars,
	of which a single one is isolated to create the Mengüçet al. micromanipula-
	tor seen in the right image attached to a silicon miroplatelet part. (Reprinted
	with permission [25]. Copyright 2011, Wiley.) (c) Jeong et al. demon-
	strated an adhesive patch composed of an array of angled nanopillars that
	could be engaged in shear (left schematic images) to transport LCD glass
	panels (right two photographs). (Reprinted with permission [5]. Copyright
	2009, National Academy of Sciences.)
1.8	Gecko inspired adhesives can be used as an enhanced medical bandage. As
	opposed to (a) conventional adhesives, (b) gecko-inspired polymer adhe-
	sives allow for air flow to the skin and peel away more easily, resulting in
	less irritation. (Reprinted with permission [10]. Copyright 2011, Wiley) 31
2.1	Scanning electron micrographs taken from an isometric viewpoint of (a)
	the round tip micropillar, (b) the flat tip micropillar, and (c) side view of
	the flat tip pillar attached to a silicon platelet part. The micropillars are
	made of elastomeric polyurethane. The white scale bars represent 50 $\mu m$
	of length

XV

- The fabrication process can be roughly grouped into three sub-processes: 2.2 (a-d) soft lithography and repeatable array molding, (e-i) isolation of a single structure, and (j-m) repeatable molding of the isolated structure. (a) Photolithography produces the initial negative SU-8 mold. (b) PDMS is cured in the negative mold to produce a positive array. (c) Silicone rubber is cured to the PDMS positive to create a soft negative mold. (d) Polyurethane elastomer with a glass backing is cured in the silicone rubber negative. (e) The positive polyure hane array is removed from the mold after curing. (f) A single pillar picks a silicon platelet part to protect the tip surface. (g) A UV ablation laser cuts a perimeter around the selected pillar into the backing layer. (h) The silicon platelet part is released. (i) The surrounding pillar array is scraped away with the tip of a scalpel. (j) What remains is a single pillar on a glass backing. (k) Silicone rubber is used again to create a negative mold of the isolated pillar. (1) Liquid polyurethane with a new glass backing is placed in the negative silicone mold. (m) The single pillar is removed after curing.
- Schematic representations of the fabrication process. a) Starting with an 2.3 SU-8 negative mold, b) we could cure the liquid polymer directly, c) to produce the positive micropillar array, and, d) finally select and isolate a single structure. e) Starting with an array of positive SU-8 micropillars, f) we first cured a negative silicone rubber mold, g) then liquid polymer was cured, h) to produce the positive array and i) select and isolate a final structure. Fabricating structures from a negative photoresist mold (a through d) results in angled pillars with *flat* tip endings (see Figure 2.1b). Replicating positive photoresist structures (f through j) results in angled pillars with round tips (see Figure 2.1a). 41 2.4 Photograph, (a), and schematic, (b), of the micromanipulation system: A load cell, B - micropillar sample, C - substrate, D - microscope objective, E - two axis manual linear stage, F - two axis manual goniometer, G motorized linear stage, H - light source. 42

- 2.6 Each column shows three corresponding images: (top row) video stills of the flat tip pillar's contact to a smooth, flat glass as seen through an inverted microscope with monochromatic green lighting; (middle row) side view video stills of the profile of the flat tip pillar as it is vertically compressed; (bottom row) side view schematics of the pillar profile during vertical compression and retraction included in order to aid in visualizing the process. The process begins when the tip barely makes contact, (a), before fully contacting the surface, (b). Additional compression causes peeling due to mechanical instability, (c), after which the tip continues to slide along and peel away from the surface, (d,e). Upon retracting, the contact patch is seen to be minimized, (f). The scale bars for each row is included in column (a), and all represent the same length: the diameter of the flat tip, 35 µm. . . . . 46

2.7 Force-distance (FD) curves of the round tip pillar obtained from indenting it onto a glass slide. FD data of the loading, at a constant compression rate of 1  $\mu$ m s<sup>-1</sup>, can be seen as the overlapped red lines flowing from left to right. The pillar was retracted at 100  $\mu$ m s<sup>-1</sup> after different distances of vertical compression were obtained, which created the separate blue lines flowing from top right to bottom left at different intervals. The schematics of the side view of the micropillar profile are based on optical microscopy observations captured via video and correlated to the empirical FD data; the schematics show the physical behavior at points of interest along the curve, highlighted by call-out boxes. Following the red FD curve from the origin (at the intersection of the dashed lines) to the point of vertical compression at (a) then retracting along the blue curve shows how to obtain a high adhesive force, i.e maximum tensile force, at point (e). The adhesive force is significantly reduced if, beginning from the origin again, you compress the pillar until it is prone, as in point (c), before retracting to point (d), where we see that only edge contact is made at the moment of separation. 47

- The flat tip pillar was compressed onto a glass slide at 1  $\mu$ m s<sup>-1</sup> then 2.8 retracted at 30  $\mu$ m s<sup>-1</sup> to create force-distance (FD) curves. Loading is graphed as overlapping red lines flowing from left to right, and retracting data is graphed as intermittently spaced blue lines flowing from the top-right to the bottom-left. The schematics of the micropillar profile are labeled to correspond directly with the information in Figure 2.6, and the schematics are mapped by call-out boxes to the points along the FD curve where the mircopillar takes the represented shape. Compressing the pillar from the origin (the intersection of dashed lines) to gentle contact at point (a), then to point (b) before retracting to point (b)\* gives a high adhesive force (i.e. maximum tensile force). Note that the shape of the pillar at  $(b)^*$ is visually identical to its shape at (b), but it is in tension, so the \* is used to denote the difference. Compressing the pillar past (b) reveals a mechanical instability from point (c) to point (d) where the tip peels away suddenly, and by compressing even further, only the edge remains in contact at point (e) before retracting to point (f) where the pillar is making minimal contact at the moment of separation.
- 2.9 The adhesive forces of flat and round tip pillars measured during pull-off from a glass substrate, after a given vertical displacement in the compressive direction, are plotted for different retraction speeds. The slowest available retraction speed of our actuator,  $1 \ \mu m s^{-1}$ , minimized the adhesive forces for both the flat tip pillar (solid red lines connecting filled circles) and the round tip pillar (dashed red lines connecting open circles). The optimal pull-off speed for the flat tip was 30  $\mu m s^{-1}$  (solid blue lines connecting filled diamonds) and for the round tip the optimal pull-off speed was 100  $\mu m s^{-1}$  (dashed blue lines connecting open diamonds). Each data point represents the median and the error bars indicate the minimum and maximum force values of three experiments. These results demonstrated how the flat tip pillar has higher maximum ratio of 35 to 1 and sharper switch between pick and release states than the round tip pillar with a maximum ratio of 26 to 1 and a smooth switch between states.

- 2.10 The adhesive forces of flat tip pillars measured at pull-off for different shear displacements and retraction speeds. Flat tip pillars where first contacted to glass with 4  $\mu$ m of compression to ensure maximum tip contact, then sheared laterally before being retracted vertically at 1  $\mu$ m s<sup>-1</sup> (plotted with red circles), 10  $\mu$ m s<sup>-1</sup> (green squares), or 30  $\mu$ m s<sup>-1</sup> (blue diamonds). Each data point and error bars represent the median and minimum and maximum force values, respectively, of three tests. The maximum pick-to-release adhesive force ratio was found to be 39 to 1.
- 2.11 A flat tip micropillar was vertically displaced 4  $\mu$ m to achieve maximum contact area of the tip or 20  $\mu$ m to induce deformation and create edge contact which minimized contact area. Retraction speeds ranged from 1  $\mu$ m s<sup>-1</sup> to 100  $\mu$ m s<sup>-1</sup>. Each data point and error bars represent the median, minimum and maximum force values, respectively, of three tests. There was a strong positive relation between adhesive force and pull-off speed when retraction started from the tip contact condition (curve plotted with a solid green line connecting circles). Retracting from the edge contact condition revealed a weak, slightly negative relation between adhesive force and pull-off speed (curve plotted with a dashed orange line connecting diamonds).
- 2.12 (a) Adhesion versus preload data shows an initial peak where tip contact is maximized and a drop off where the fibers bend sufficiently to remove the tips from contact with the substrate. The plateau after the drop off is where the sides of the fibers are in contact. (b) Taking the fraction of the maximum measured adhesion force over the minimum measured adhesion force for the same retraction velocity gives the adhesion control ratio. The highest control ratio observed, 30:1, was at retraction speeds of 30  $\mu m s^{-1}$ . 54
- 2.13 Video snapshots from an inverted microscope show the steps of pick-and-place manipulation of the silicon microplatelets: (a) The micromanipulator contacts the first part, (b) picks it up from the substrate, and (c) brings the first part in contact with the second. (d) Compressive vertical displacement bends the pillar. (e) The pillar is slowly retracted. (f) The microassembly is completed.

51

- 2.14 Figure of video stills from a demonstration of the macroscale manipulation capability of a 10x10 array of round tip micropillars. The cover slip has been outlined and schematics representing the deformed state of any given pillar have been included to guide the reader. (a) The array is vertically displaced to sufficiently compress it to form a large contact before (b) retracting rapidly and picking up the glass cover slip. (c) When brought into contact again, vertical displacement control is utilized to compress the array of round tip pillars and induce edge contact, (d) such that retracting the array slowly will enable the cover slip to be released.

- 2.16 These side view video stills of the fiber shows the shape as the fiber displaces due to the preload. White outlines and highlights have been added to help visually define the shape of the fiber and contact substrate. . . . . . 63
- 2.17 As the load increases from (a) to (d), the actual contact area, highlighted in white, first increases, (b), then decreases, (c), and finally disappears, (d).65

2.18	A side view schematic of the geometrical considerations in the model of	
	the contact process of the round tip pillar. The curvature of the round tip, $\rho$ ,	
	defines the size of an imaginary sphere with which the tip is circumscribed.	
	The contact patch of this imaginary sphere as predicted by the JKR theory	
	is $R_{JKR}$ . The actual area of the tilted pillar tip (tilt angle is $\theta$ ) as projected	
	to the contact plane is $R_{tip}$ . The lateral displacement of the tip due to	
	loading is $\delta_x$ .	66
2.19	A top view schematic of the geometrical considerations in the model of the	
	contact process of the round tip pillar. The contact patch of this imaginary	
	sphere as predicted by the JKR theory is $R_{JKR}$ . The actual area of the pillar	
	tip as projected to the contact plane is $R_{tip}$ . The lateral displacement of the	
	tip due to loading is $\delta_x$ .	68
2.20	A representative adhesion versus preload curve (30 $\mu ms^{-1}$ retraction ve-	
	locity) is compared to the simulated contact area which is normalized to	
	the maximum contact area	69
2.21	Finite element modeling of the angled flat tip micropillar reveals that the	
	"toe" section of the tip surface is under tensile stress when the vertical	
	displacement applied at the backing is compressive. The plotted lines are	
	labeled with vertical displacement values and shaded from light to dark to	
	represent low to high degrees of compression. The insert shows a schematic	
	of the pillar under loading conditions with dashed grey lines indicating how	
	cross sectional position is mapped on the tip	71
3.1	(a) SEM image of an array of small micropillars with large contaminat-	
	ing particles, and (b) the same array after dry self-cleaning against a glass	
	substrate, showing that the contaminating particles embed to the backing	
	layer. (c) Medium pillars contaminated with particles of similar size, and	
	(d) after partial cleaning. (e) Large micropillars contaminated with much	
	smaller particles have most of the contamination on the tips, but (f) after	

self-cleaning, most of the particles are embedded in between the array. . . 77

3.2	Micrographs of the three sizes of micropillars used in this study, with di-	
	mensions in microns. (a) The small micropillars are 25 $\mu$ m in height and	
	20 $\mu$ m in diameter at the tip, (b) the medium pillars are 50 $\mu$ m in height and	
	30 $\mu m$ in diameter at the tip, and (c) the large micropillars are 105 $\mu m$ in	
	height and 95 $\mu$ m in diameter at the tip. The scale bar in the lower right is	
	the applicable to all three micrographs.	78
3.3	(a) Computer model rendering of the adhesion testing system built on an	
	inverted view microscope. (b) Close up of the model rendering and the	
	(c) photograph of the actual testing system show labeled components: A -	
	goniometer, B - manual x and y axes stages, C - motorized y axis stage, D -	
	load cell, E - light source, F - adhesive sample, G - glass contact substrate,	
	H - microscope objective.	79
3.4	(a) Contamination is carried out by moving the array of micropillars into	
	contact with a monolayer of microspheres dispersed on a glass slide. (b)	
	The cleaning process is conducted by pressing the array into a clean patch	
	of a glass slide, then displacing the glass substrate laterally before retract-	
	ing the array. (c) Adhesion measurements are taken after each cleaning	
	cycle against a clean patch of a glass slide.	81
3.5	(a) Microscopy images of the array of large micropillars contaminated with	
	small spheres (Regime 3) during a cleaning cycle shows how the pillars col-	
	lapse and the backing layer deforms due to the applied shear displacement.	
	The final image is a background-subtracted micrograph of the contact sub-	
	strate showing the residue of deposited microspheres. (b) Images of the	
	same size of micropillars contaminated with much larger particles (Regime	
	1) shows that the sphere makes contact with the glass substrate and is rolled	
	off of the tips of the micropillars, leaving a clean array in the final inset im-	
	age. The arrows indicate the direction of motion of the contact substrate.	
		82
3.6	Schematic of the two modes of self-cleaning observed: (a) embedding par-	
	ticles into the array of adhesive structures, and (b) deposition of the parti-	
	cles to a clean substrate.	83

3.7	Self-cleaning is dependent on the relative sizes of contaminating particles	
	and the characteristic length of the micropillars. The characteristic length	
	can be (a) the tip radius, (b) the length of the fiber, or (c) the spacing be-	
	tween fibers. In the case of tip-radius dependency, we defined three regimes	
	for when: (R1) the particle radius is greater than twice the tip radius, (R2)	
	about the same size, and (R2) less than half the tip radius. $\ldots$ $\ldots$ $\ldots$	84
3.8	This graph of cleaning coefficient versus cleaning cycles shows that dif-	
	ferent regimes of particle and micropillar sizes results in different rates of	
	adhesion recovery and different saturation points	86
3.9	This graph represents the contamination resistance within the different size	
	regimes as determined by particle diameter and micropillar height. In	
	regimes 1 and 2 and in the case of the flat, unstructured surface, the parti-	
	cle diameter is large enough to physically block the micropillars' tips from	
	contacting the glass slide. In regime 3, the mushroom shaped tip of the mi-	

cropillar conforms around the dirt particle to make contact with the glass

- 3.11 (a) An adhesive patch of micropillars will require a lateral dragging distance greater than or equal to the patch length. (b) If the adhesive patch is split into a hierarchical array of micropillars on top of macropillars, then the required dragging distance will be reduced to an amount greater than the length of an individual macropillars.

4.1	The graph shows how the tip of the fiber relaxes back to its initial config-
	uration after being bent due to large compressive loads. The micrographs
	show the position of the tip at the beginning (A) and end (B) of the graph's
	data range
4.2	This schematic represents the contact process for the next generation mi-
	cromanipulation system. (a) Arrays of micropillars smaller in size than
	the pars to be manipulated are brought into contact before (b) the tips are
	engaged by shearing the adhesive array and (c) the parts are lifted off the
	donor substrate. Either (d1) shear displacement control or (d2) vertical dis-
	placement control is used to (e) release the parts to the receiver substrate.
4.3	This graph shows how with even slight misalignment, the adhesion force
	of an array of micropillars can be reduced almost by half
4.4	An SEM image of the lamellae adorning the toes of geckos. The results
	from our self-cleaning research suggest that lamellar structures may ac-
	tually aid in adhesion recovery by leaving a space for dirt particles to be
	trapped, away from the tips of the adhesive structures. (Copyright Cliff
	Mathisen, FEI Company)
A.1	a) Photograph of Waalbot with components labeled and an inset of an SEM
	image of the gecko-inspired dry fibrillar adhesives used in the footpads; b)
	Details on naming conventions used for the leg and its components 106
A.2	CAD diagrams showing the stepping process for a forward step (leg rotat-
	ing clockwise in image). a) Two feet (A and B) are in contact; b) Foot A is
	peeled from the surface; c) Foot A releases from the surface and the robot
	begins to move forward; d) Foot C rotates closer to make contact with the
	surface; e) Foot C achieves contact with the surface and now foot B is the
	rear foot. The process continually repeats for forward movement

A.3	Still image frames from a video of the robot climbing from the floor (a) to
	the wall (b,c,d), transferring to the rear wall (e,f), and then transferring to
	the ceiling (g,h) of an acrylic cube. The robot path is illustrated in (a) with
	an overlay. A weight is hung in the top corner for reference to show that
	the direction of gravity is down
A.4	a) Plot showing force data from the two tail force sensors while the robot
	climbs on a smooth, vertical surface; b) the robot starts out with sufficient
	adhesion to maintain attachment; c) On the second step, the right side loses
	adhesion and detaches from the wall. The robot continues moving side-
	ways, stepping with both feet, but only the left side has sufficient adhesion
	and the right side continues to slip
A.5	Simulated length scale effect on a climbing robot's theoretical factor of
	safety. With increasing payload masses, the optimum size of a Waalbot
	increases. The shaded region along the bottom is where the theoretical
	factor of safety is below 1. The dots represent the calculated factor of
	safety for various types of pad-bearing lizards as adapted from [26] 110
A.6	Small-scale Waalbot climbing inside an acrylic cube with 30 cm sides
	demonstrating: a) climbing down a wall; b) transitioning from a wall to
	the floor; c) crawling across the floor; d) floor-to-wall transition; e) vertical
	wall climbing; f) wall-to-wall transition; g) steering on a wall; h) wall-to-
	ceiling transition; i) inverted steering; j) inverted climbing. $\ldots \ldots \ldots \ldots 111$
A.7	Free body diagram showing the forces present during a forward step on a
	surface at angle $\psi$ where the front foot is pressed against the surface and
	the rear foot is being peeled. $F_{RX}$ and $F_{FX}$ are the rear and front forces,
	respectively, in the X direction. $F_{RN}$ and $F_{FN}$ are the rear and front forces,
	respectively, in the normal , Y, direction. $F_T$ is the tail force, while W is
	the weight of the robot acting on the center of gravity
A.8	Possible mechanism of adhesion increase during rocking motion: a) Illus-
	tration showing a piece of dirt that inhibits surrounding fibers from en-
	gaging with the surface; b) More fibers can engage with the surface when
	repeatedly loaded and unloaded during rocking maneuvers

A.9	Illustration showing the setup to examine the effect of a rocking motion	
	using constant preload	. 115
A.10	Experimental results showing the increase in adhesion when the number of	
	rocking maneuvers is increased, when rocking using a constant preload	. 116
A.11	Plot showing the force on the feet over many steps as well as the increase	
	in adhesion due to regain adhesion events. When the force on the tail sen-	
	sor drops below 0.325 N, the adhesion regain event is triggered and the	
	adhesion then increased on the subsequent step	. 117
A.12	Overview of the 2-level motion planner: a) Waypoints are generated along	
	transitionable plane intersections and connected; b) Trajectories are gener-	
	ated to plan a path between the waypoints. The relative orientations of the	
	wall, floor, and ceiling is arbitrary.	. 118
<b>B</b> .1	(a) Schematic of the classic experiment to visualize Newton's rings [27].	
	(b) The fringes are a result of interference of the reflected light from the	
	planar and hemispherical surfaces. The center of the dark band where de-	
	structive interference is seen indicates a region where the two surfaces are	
	separated by an integer number of wavelengths, $n\lambda$ . The center of the light	
	bands where constructive interference is seen occurs where the surfaces are	
	separated by some number of half wavelengths, $\frac{n}{2}\lambda$ .	. 122

Chapter

## Introduction to Gecko-Inspired Adhesives

## 1.1 Motivation

The discovery of the gecko's remarkable foot adhesion has provided a riddle for engineers and scientists to solve: how can an adhesive surface be selectively sticky, directional, remain clean and work on almost any material? Geckos feet stick to almost anything, in almost any condition (including underwater and in space), but do not stick unintentionally, do not stick to dirt, and enable the gecko to literally run up the walls. When climbing a smooth surface geckos are attaching and detaching each foot very quickly (detaching a foot takes 15 milliseconds) and with almost no noticeable force, but if attached perfectly they could theoretically hold tens of times their body weight. In contrast to gecko adhesion, conventional adhesives, made of soft tacky materials, tend to leave residues, pick up dirt easily, stick to themselves strongly and are useless underwater. Gecko feet rely on a completely different principles, utilizing arrays of tiny mechanical structures made of very stiff protein which react to pressing and dragging with some very smart behavior. A gecko's adhesive pads exploit principles of friction and adhesion in a way that was completely against intuition, which as a community we have only begun to understand and mimic through synthetic analogs. Geckos have evolved finger tips which are covered in tiny structures which make a comparatively vast area of contact with opposing surfaces, and attach very strongly as a result. However, this is just the beginning of the principles seen in gecko adhesion and we must ask ourselves: What are the principles of adhesion and friction that geckos



exploit? And perhaps more importantly: how can we make synthetic gecko adhesives?

Figure 1.1: (a) A series of images showing the ever smaller attachment structures of the gecko, from its foot down to the hair-like setae that cover the bottom of each toe, and the spatulae that terminate the tips of the setae. (Reprinted with permission [1]. Copyright 2006, Springer.) (b) One of the first SEM images of gecko setae taken in 1965 by Ruibal and Ernst (Reprinted with permission [2]. Copyright 1965, Wiley.) (c) An SEM image of the entire setal stalk clearly showing asymmetric morphology. (Reprinted with permission [3]. Copyright 2006, Company of Biologists.) (d) Hierarchical polymer microstructure with mushroom tip and backing layer noted. (Reprinted with permission [4]. Copyright 2009, American Chemical Society.) (e) Hierarchial polymer structure composed of angled nanopillars molded on top of vertical micropillars.(Reprinted with permission [5]. Copyright 2009, National Academy of Sciences.)

This chapter will review the principles of gecko adhesion, the structures and mechanics derived from these principles, the manners in which engineers and scientists have created gecko-inspired adhesives, and finally, the applications which are possible thanks to these adhesives. Our goal is more to motivate and inspire than to exhaustively list every one of the hundreds of papers on gecko adhesion in the canon. To that end, our primary emphasis is to explain the general principles of gecko adhesion without delving too deeply into the theoretical mechanical proofs of their operation. We will also explain how to make synthetic adhesives and the benefits and challenges of the different approaches that have

emerged. Fabrication is an open problem in the field, and moving forward it is clear that as of yet unconsidered approaches may provide additional benefits. Finally, we want to motivate the field as a whole, not just from the source of a scientist's curiosity, but also from an engineer's sense of urgency in applying what we have learned to problems that seem intractable. Although there is only a small body of literature describing applications in robotics and medical devices, the number of possibilities is growing and applications will become more convincing as our understanding of gecko adhesion improves and our ability to synthesize gecko adhesives is refined.

There are several other recent reviews of the field of gecko adhesives which cover certain topics in greater depth. Each has its own focus and varies in the breadth of the review. The most recent overview of the field can be found in Jagota and Hui's article [28], with special emphasis on the theory of gecko adhesion and friction. A review of structures and adhesion testing protocols is highlighted by Boesel et al. [29] and by Sameoto and Menon [30]. A concise introduction to the mechanisms of gecko adhesion is to be found in Kamperman et al. [31]. Majumder et al. have a recent book chapter that looks at mechanisms of adhesion and fabrication methods [32]. Kwak et al. reviewed a variety of approaches to fabricating controllable, nanoscale fiber arrays [21]. From a different perspective, an overview of the discoveries of gecko adhesion from a biologist's perspective can be found in Autumn's review article [33].

#### A note on terminology

Let us take a moment to clarify several terms that are used in the field but may seem confusing or arbitrary. Gecko adhesion, or structured adhesion, refers to the principles of attachment based on intermolecular forces of a surface characterized by arrays of structures. Covering the bottoms of gecko feet are billions of long, thin fibers, called setae which branch into even smaller structures at their tips, called spatulae (see Figure 1.1a). Since gecko setae have aspect ratios greater than 10, i.e. the length is ten times greater that the diameter, it is appropriate to call them fibers or fibrils. However, it seems more appropriate to call short, squat, man-made structures pillars or posts, if they have aspect ratios less than 10. We use the prefaces nano, micro, and macro when the critical dimension of an

object (e.g. the diameter of a fiber) is between 1 and 1000 nm, 1 and 1000 µm and over 1 mm, respectively. The backing layer of a synthetic gecko-inspired adhesive refers to the flat, unstructured layer of polymer on which the array of fibers or posts is formed (see Figure 1.1d). Hierarchical structures are those that integrate multiple size scales of structure along multiple levels, e.g. the gecko setae split into clusters of smaller fibrils each of which in turn end in a flattened plate called a spatula. Adhesion strength and adhesion pressure refers to the ultimate strength of attachment, that is, the average stress across the interface exhibited just before the separation of two surfaces in contact. Adhesion or attachment force, used interchangeably, refers to the ultimate force required to separate two surfaces, irrespective of the contact area. We use the term adhesion when the motion of the surfaces being separated is perpendicular to the surfaces, but we use the term shear or friction to describe motion parallel to the surfaces. As such, shear strength and shear force are defined similarly their adhesion counterparts. The definition of work of adhesion gets a good treatment in Jagota and Hui's review, but we will use the term only in the sense of the energy required to separate surfaces in contact [28].

## **1.2 Biological Inspirations**

The ability of some lizards to climb smooth flat surfaces has been of noted interest since Aristotle's time [34] and the fine structures on gecko feet have been closely documented by naturalists starting over a century ago [35]. The first scanning electron microscopy (SEM) image of climbing lizard adhesive structures taken by Ruibal and Ernst in 1965 revealed tiny branching hierarchical fibers called setae [2] (see Figure 1.1b). Until recently the exact mechanisms of attachment were unclear, but early studies by Hiller [36] lead to inferences that the principles were based on intermolecular surface forces. Irschick et al. [26] found that among climbing lizards there was a strong correlation between adhesive pad size and attachment strength when normalized to body mass, but a weak correlation between pad size and body mass. This suggested that there was an additional factor that related body size to attachment strength, which turned out to be the size of the setae [12]. Arguably, the most influential description of the fundamental mechanisms of attachment is found in the seminal work by Autumn et al. from 2000 [37], where the adhesive force of a single seta

#### 1. Introduction

was measured and evidence was provided to support the theory that van der Waals forces were the primary source of attachment strength [36].

In addition to the nature of the adhesive forces, the mechanical principles of attachment were unclear until studies revealed the importance of the loading conditions on adhesion of the gecko's feet [8, 38, 39]. The gecko activates the adhesion of its foot pads by dragging them along a surface in a particular direction, which bends the tiny hairs covering its toes, causing the tips of the hairs to press into contact against the surface. As long as a dragging force is applied (even if no dragging motion occurs), the hairs remain in contact, but when the gecko begins to move its foot in the opposite direction, the hairs disengage and the adhesive pads are easily removed from the surface. Such a simple and rapid adhesion control enables the gecko to run up a wall at almost  $1 \text{ m s}^{-1}$ .

## 1.2.1 Key discoveries in gecko adhesion

After the initial proof of attachment principles from Autumn et al. [37], an explosion of subsequent work attempted to discover the exact mechanisms and potentials of synthetic gecko adhesives. Autumn and Peattie [38] showed that by pulling a seta at a certain angle, the attachment force was reduced to zero. Autumn et al. also showed that the attachment strength of gecko setae is strongly coupled with shearing loads, a phenomenon called frictional adhesion [8]. Arzt et al. found a strong inverse relationship between the mass of a climbing animal and the characteristic size of the attachment structures on its feet [12] (see Figure 1.3), suggesting that finer structures provide stronger adhesion which answers the questions raised in the earlier work by Irschick et al. [26]. Stork further correlated the attachment strength of geckos with the number of adhesive structures on their feet [40]. Hansen et al. characterized the incredible fact that gecko adhesives are self-cleaning, i.e. through attachment-detachment cycles, they can regain adhesive strength after contamination by dirt [11]. What is so incredible about the property of self-cleaning is that it is unexpected that an adhesive that can attach so strongly to a surface would simultaneously and selectively expunge contaminating particles from itself.

The exact source of attachment strength continues to be debated, a controversy highlighted by the number of papers attempting to characterize the contribution of van der Waals and capillary forces to gecko adhesion. In 2002, Autumn et al. [7] showed that van der Waals, not capillary, forces were the dominant attachment forces. However, in a series of papers, researchers conducted adhesion experiments using atomic force microscopy (AFM) that showed capillary forces might be a significant contributor to adhesion [41, 42, 43, 44]. Subsequently, characterization of the effect of humidity on the elasticity of  $\beta$ -keratin, the protein that setae are made of, helped to explain changes in adhesion while maintaining that van der Waals are the dominant attachment forces [45, 46]. In a possibly critical discovery, it was recently shown that geckos actually leave footprint residues of phospholipids, despite the fact that geckos are not known to have secretion glands in their feet [47]. It is still unclear what impact the discovery of gecko footprints will have on our understanding of the fundamental principles of gecko adhesion, since most theories that have been developed to explain gecko adhesion are predicated on a dry contact interface.

### **1.2.2** Structured adhesion in other animals

Micro-scale features can be found on the feet of many different species of climbing animals, which indicates that structured adhesion was evolved repeatedly and separately through the phenomenon of evolutionary convergence as a solution to the problem of attachment [48, 49, 50]. Beatles use sustained attachment strengths 60 times their body weight in an impressive display of passive defensive capabilities, preventing ants from carrying them off [51]. However, it is interesting to note that while the gecko uses "dry adhesion," insects and frogs secrete liquids to utilize wet adhesion to augment the attachment strength of the arrays of microstructures. Insects' adhesive secretions have been observed in a wide range of cases [51, 52, 53, 54, 55, 56]. Tree frogs' adhesive structures more resemble flat pancake like structures, with a significant contribution to attachment arising from capillary forces [57].

### **1.2.3** Summary of observed principles of micro-structured adhesives

Autumn proposes that there are seven principles of gecko-inspired micro-structured adhesives that makes them so inspiring and impressive as an engineering device: anisotropic

#### 1. Introduction

attachment, high pull-off force to preload force ratio, low detachment force, material independence due to van der Waals adhesion, self-cleaning, anti-self-matting, and non-sticky default state [6] (see Figure 1.2). Generally speaking, these principles have been found to exist in natural adhesive pads that possess fibrillar structures with flat spatular tips [58]. As is the case for all human technology that mimics or is inspired by biological examples, the adhesive structures we see on the gecko's foot serves as an "existence theorem" [28] which shows us a path to take to achieve similar performance in our own synthetic adhesives.

The gecko's adhesive pads have shown us that it is possible to have several seemingly contradictory properties exhibited on a single structured surface [33]. We have seen that heavier animals have finer structures in their adhesive pads, which leads to the conclusion that increasing the number of discrete contacting structures, even if each individual structure is smaller, holds a significant benefit for increased attachment strength [12, 38] (see Figure 1.3). The principles of frictional adhesion described by Autumn et al. indicate that the gecko only adheres if it slides its feet or maintains a shear force along a surface [8, 38]. Subsequent models by Gao et al. showed that the asymmetric, angled structure of the gecko setae explains the need for shear to maintain attachment strength [59], and in fact, this requirement turns out to be a feature, because it allows for rapid attachment and detachment [39].

The adhesive structures have an added benefit in that they increase the compliance of the interface as a whole. The  $\beta$ -keratin which composes the setal arrays has been characterized to have a high elastic modulus, with stiffness on the order of 1-3 GPa [60, 61]. However, when formed into arrays of compliant, high aspect ratio fibrils, the interface exhibits an effective elastic modulus of 100 kPa, a four orders of magnitude reduction in stiffness [8]. Persson used a simple model that addresses the structural difference between the bulk  $\beta$ -keratin and the array of setae to confirm the mechanism behind this increased compliance [62]. Interestingly, this increased compliance approaches the critical value of stiffness called the Dahlquist criterion which was originally set forth as the stiffness that unstructured pressure sensitive adhesives need to attain in order to exhibit the necessary tack to adhere well [63]. This criterion derives from the balance of forces that an adhesive material experiences: the attraction between the contact substrate and the adhesive material due to van der Waals forces and the repulsion from elastic forces restoring the deformed



Figure 1.2: The seven principles of gecko adhesion as outlined by Autumn [6] are presented here with representative observations from literature. (a) Evidence for van der Waals forces, as opposed to capillary forces, is shown by the equivalent attachment forces of a gecko foot to hydrophobic GaAs and hydrophilic SiO<sub>2</sub> surfaces. (Reprinted with permission [7]. Copyright 2002, National Academy of Sciences.) (b) High adhesion and friction forces are achieved for low preloads when the gecko foot is dragged in the direction of the curvature of the setae. (Reprinted with permission [8]. Copyright 2006, Company of Biologists.) (c) Easy detachment of the gecko foot is observed if it is dragged against the curvature of the setae. (Reprinted with permission [8]. Copyright 2006, Company of Biologists.) (d) The anisotropic attachment of the gecko foot is replicated in a patch of synthetic adhesive composed of angled pillars with angled mushroom tips. The inset images show microscopic deformations of the individual micropillars under directional loading. (Reprinted with permission [9]. Copyright 2009, Wiley.) (e) In their default, undeformed state, the gecko setal array is highly non-sticky, which is visually represented here by its superhydrophobic contact with a water droplet. (Reprinted with permission [1]. Copyright 2006, Springer.) (f) Gecko setae have evolved to be non-matting, but man-made synthetics need to be optimized, as can be seen here where the top image shows free standing micropillars, but in the bottom image the pillars are matted together. (Reprinted with permission [10]. Copyright 2011, Wiley.) (g) Even when a gecko's foot becomes completely saturated with dirt, after just a few simulated steps it can regain a large portion of the original attachment strength; these SEM images show the dirty and after cleaning states of a setal array. (Reprinted with permission [11]. Copyright 2005, National Academy of Sciences.)

materials to their original shapes.

In the following section we will delve into the mechanisms of gecko adhesion, and look at the models that explain the principles that we observe in nature.

## **1.3** Mechanical Principles of Structured Adhesives

### 1.3.1 Adhesion

#### **Contact splitting**

The observation that animals with greater body mass have adhesive structures with smaller dimensions seems counter-intuitive, but the reason behind it can be described nicely with an adhesive contact model. Hertz described how the contact between an elastic sphere and a rigid plane is related to the applied compressive force [64], and Johnson, Kendall and Roberts (JKR) showed that by including the adhesive forces present between the contacting objects, a tensile load could also be modeled [65]. In predicting the adhesive force of the sphere and the plane, the parameters of the JKR model are the radius of the sphere, *R*, and the surface energy of the interface,  $\gamma$ .

$$F_{JKR} = 1.5\pi R\gamma \tag{1.1}$$

Autumn et al. and Arzt et al. used this contact model to demonstrate how reducing the size of the individual structures while increasing the quantity actually increases the total tensile load the interface can bear [12, 38]. Arzt et al. found that if the structures are split into N parts, and their characteristic size is split as  $R/\sqrt{N}$ , then the total pull-off force of N structures, each with a force of  $1.5\pi R\gamma/\sqrt{N}$ , becomes

$$F_{total} = \sqrt{1.5N\pi R\gamma} \tag{1.2}$$

However, there is a limit to this model, as Tang et al. and Gao et al. point out [59, 66]. You cannot obtain infinite force by splitting a contact *ad infinitum* because there is an upper bound set by the theoretical strength of the van der Waals force, a limit that the gecko appears to have hit [37]. That being said, it is important to note that the original insight is
quite instructive and the limiting bound occurs at length scales below 100 nm, and based on this principle, a significant mass of work has emerged extolling the benefits of contact splitting for adhesion [14, 67, 68, 69, 70, 71, 72, 73, 74].



Figure 1.3: Arzt et al. found a relationship between the mass of climbing animals and setal density, i.e. the number of individual structures present on a given surface area of the foot. This discovery reveals that heavier animals have smaller setae, and more of them. (Reprinted with permission [12]. Copyright 2003, National Academy of Sciences.)

# **1.3.2** The importance of the terminal tip geometry

At length scales on the order of van der Waals interaction distances (1 to 100 nm), the effect of the tip geometry becomes negligible [66, 75], but at the length scales of most synthetic gecko adhesive structures (1 to 100  $\mu$ m), the tip geometry is much more important. Del Campo et al. [76] conducted a systematic empirical analysis of the importance of length scale and tip shape on adhesion and found that for the range of pillar diameters from 2.5 to 25  $\mu$ m, the change in pillar length had a one order effect on pull-off forces, but changes in tip geometries had a two order of magnitude effect. Pillars with mushroom shaped tips had the greatest pull-off force, a finding that was contemporaneously and subsequently observed in several other instances [9, 14, 70, 76, 77, 78, 79] (see Figure 1.4 for different tip geometries).

Mushroom shaped tips have been observed to detach in an interesting manner: whereas plain, cylindrical fibers exhibit crack propagation from their edges inward, in mushroom tipped fibers, cavitation initiates crack propagation from the center outward [70]. This effect is related to the stress distribution on the tip surface. Carbone et al. [80] suggest

through numerical modeling that the thickness of the mushroom tip can be optimized to reduce stress singularities at the interface of the fiber and contact substrate. The mushroom tip is also observed to be important for contamination-resistance and wet self-cleaning of the synthetic adhesive array, but in two very different ways. For dry contamination-resistance, the compliance of the mushroom tip allows it to conform around small particles at the tip-surface to contact-surface interface [14]. For wet self-cleaning, when water droplets are poured onto an array of pillars with mushroom shaped tips, the water stays on the tip surface and does not wet in between the fibers [78]. This allows the droplet to pick up contaminants and roll away when the array is tilted, identical to the wet self-cleaning of lotus leaves where arrays of microstructures create a hydrophobic surface.

If the mushroom tips were to be expanded in diameter, one can imagine them eventually forming together into a thin film of material held up by the array of posts underneath. Exactly such structured surfaces composed of continuous terminal films along the tops of a pillar array have been demonstrated to exhibit the benefits of crack trapping while maintaining a larger contact area than standard fibrillar arrays [81, 82, 83, 84]. Although the film terminated arrays show better adhesion to rough surfaces than unstructured flat adhesives [85], there are no comparative studies examining the relative performance of film terminated and mushroom tipped fiber arrays.

# Matting condition as a limiting principle

The matting condition, also called lateral collapse, is the principle where compliant, high aspect ratio fibers have the tendency to cohere to their neighbors. One can consider the matting condition to be governed by the ratio of the attraction energy between neighbors in contact and their respective stored elastic energies. In a pair of companion papers on the design of fibrillar contacts, Glassmaker et al. proposed a governing equation of lateral collapse [86], and Hui et al. showed that this collapse can significantly and negatively affect adhesion [68]. For these reasons, matting sets a boundary to the design space of structured adhesives, and has been addressed in other models [87, 88, 89] and experiments [90] in order to confirm and refine our understanding of this limiting condition.

### Flaw insensitivity

The concept of flaw insensitivity describes how the stress distribution of fibers approaches the theoretical limit of interfacial attachment strength as the size of the fiber approaches the length scale of the interaction distance of the van der Waals force [66]. Flaw insensitivity is described by a dimensionless parameter,  $\chi$ , which is related to the theoretical interfacial attachment strength,  $\sigma_0$ , the elastic modulus of the fiber, *E*, the radius of the fiber, *r*, and the distance over which interfacial cohesive forces are effective,  $\delta_0$ :

$$\chi = \frac{\sigma_0 r}{2\pi E \delta_0} \tag{1.3}$$

This parameter can be considered as a ratio of the fiber radius to interfacial force distance. It shows us that for softer fiber materials the radius must be reduced to maintain an equivalent adhesive strength, but soft, thin fibers lead to matting and lateral collapse, which we consider in more detail below. When  $\chi$  is much smaller than 1, then the fiber is considered to be flaw insensitive and the average stress at the interface will equal the theoretical limit of the interfacial attachment strength. For cases where  $\chi$  is much larger than 1, the fiber is flaw sensitive and will behave according to classic contact mechanics [68]. Furthermore, it is important to remember that for small length scales the tip shape is less important, but at larger scales the tip shape is critical [75].

#### The effect of surface roughness

So far we have addressed the major principles in the interaction of a structured adhesive with a contact surface, but the presented theories generally assume smooth contact surfaces whereas, with only a few exceptions, surfaces are rough. The first attempt at considering roughness in gecko adhesion was done by Persson where he proposed a model of the energetics of a system of a fibrillar interface in contact with a rough surface [62]. Additionally, Persson and Gorb modeled the ability of the flat plate-like spatulae that terminate the tips of gecko setae to adhere to rough surfaces [91]. Subsequent models attempt to address the benefits of added compliance of a fibrillar interface when contacting a rough surface [88, 92, 93]. Bhushan et al. modeled the effect of hierarchy to suggest that different levels allow for compliance to different wavelengths of a randomly rough surface [88].

Schargott et al. created a model that highlights the independent action of fibers when contacting a non-flat surface as an assumption of analogy to fractally rough surfaces [92]. Hui et al. found that with increasing roughness, the pull-off forces of a fibrillar interface decreases, but increasing fiber compliance can mitigate this effect [93].

Experimental analysis of the effects of roughness is less common. Lin et al. demonstrated that mechanically tunable ripples on a soft flat surface can affect adhesion [94], and Vajpayee et al. showed that a film terminated fibrillar array retained some adhesive performance to a rough surface even when a flat control lost all adhesion [85]. The analysis most relevant to gecko-like adhesive structures was recently conducted by Caas et al., where they showed that micro-patterned surfaces failed to adhere to roughnesses at scales much smaller than and much larger than the fiber size [95]. These theoretical and experimental results suggest that hierarchy is critical for adaptation to a wide spectrum of roughness scales.

### **Additional principles**

We have covered the principles that demonstrate the most dominant and universal effects on adhesion, but secondary considerations have come into focus after these primary effects have been identified. The additional principles affecting adhesion that we will review include fiber stochasticity, liquid interfaces, backing-layer thickness, fiber viscoelasticity, and soft surface adhesion.

A gap has existed between experimental results of the nanoscale contact of a single setae [41] and macro-scale tests of a complete gecko-inspired adhesive surface [26]; statistical modeling attempts to bridge these scales [96, 97, 98]. Hui et al. demonstrate that statistical modeling of a fibrillar interface can capture an important principle: the averaged adhesion strength of an array of setae is less than the adhesion strength of a single seta, but the variance of the array is also smaller [96]. A subsequent statistical study by Porwal and Hui introduced more realism to the model [97], and experimental results by McMeeking et al. showed that greater variance in fiber sizes results in reduced adhesion [98].

Though we have been focusing on dry adhesion, Vajpayee et al. [85] presented evidence that structured adhesives can perform equally well underwater, and Lee et al. [99] and Glass et al. [100, 101] showed that the addition of a mussel-inspired surface coating to the tips

of the fibers can greatly improve under water adhesion. Cheung et al. showed that an oil layer on the tips of the fibers can also improve adhesion, but that the improvement was dependent on the thickness of the oil layer [102].

The thickness of the backing layer for a structured interface has generally been neglected, but a model by Long et al. [103] and experimental results by Kim et al. [104] clearly show that it is a significant contributor to the pull-off force. The highest pull-off force of a flat silicon disk from an array of mushroom-tipped micropillars was achieved when the backing layer thickness was less than half of the disk radius. The observed pulloff forces decreased sharply for cases where the backing layer thickness was greater than half of the disk radius. The enhanced adhesion force was due to equal load sharing, when each micropillar experienced the same load, and decreased adhesion force occurred due to stress concentration, when the backing layer deformed and micropillars along the edge of the disk contact experienced higher stresses.

The aspect ratio of the adhesive pillars plays an important role in the stress distribution on the tip surface and subsequent adhesion characteristics. Aksak et al. [105] used finite element modeling to predict that lower aspect ratio pillars will have higher pull-off forces, but will also become stiffer and more sensitive to defects at the interface. In a seemingly contradictory result, Greiner et al. [106] found through an experimental study that tall, thin structures were significantly more beneficial to increasing adhesion. This contradiction is understandable when one considers that Aksak et al. modeled a smooth pillar tip contacting a perfectly smooth surface, and that any experimental system, as in the Greiner et al. study, will have surface roughness which introduces defects and crack nucleation points.

It is becoming clear that the static models that have been used to describe the principles of structured adhesives fail to capture the important rate-dependent properties present. In Shull's review of the subject, he presents the past four decades of viscoelasticity models that have attempted to revise the original contact mechanics proposed by the JKR model [107]. Rate dependency of pull-off forces has been exploited in a transfer printing scheme using flat unstructured elastomeric surfaces by Meitl et al. [108]. Subsequent introduction of structuring by Kim et al. greatly amplified the effects of rate dependency [24]. Crack propagation has been linked to the rate of pull-off and the pull-off force by Vajpayee et al. for thin film terminated fibers [109], and Castellanos et al. showed an increase in the

adhesion of a fibrillar array for increasing pull-off speeds [110]. The consideration of rate of loading in adhesive strength is significant because it may define how synthetic gecko adhesives should be used in such applications as climbing robots, robotic micromanipulation, and medical adhesives.

Finally, a note should be made on soft-substrate adhesion. Nearly all experimental results and theoretical models apply to gecko-adhesives contacting a stiff material such as glass, but recent works have revealed there is significant potential for gecko-adhesives to be applied to skin. Mahdavi et al. demonstrated that a microstructured adhesive made of biodegradable polymer could be adhered to tissue in vivo, a step towards replacing staples and sutures with gecko-adhesives [111]. Cheung and Sitti showed that arrays mushroom-tipped micropillars had better adhesion than flat unstructured polyurethane when in contact with a soft hemisphere with a Young modulus similar to skin (200 kPa) [112]. Kwak et al. replaced traditional acrylic adhesives on medical diagnostic electrodes with mushroom-tipped micropillars in a demonstration of a potential near-term application [10]. Karp and Langer have recently highlighted the potential for novel medical applications of gecko-adhesives [113]. However, it is clear that there is significant work to be done to improve the attachment strength to soft, oily substrates like skin, and to resist contamination by dead cells and tissue.

# 1.3.3 Friction

### Classic friction theory for smooth flat surfaces

Our current model of friction between non-adhering, smooth, flat surfaces is based on the Amontons-Coulumb law [114], which is easily recognizable:

$$T_{max} = \mu_S N \tag{1.4}$$

where  $T_{max}$  is the maximum applied shear force before sliding,  $\mu_S$  is the coefficient of static friction and N is the applied normal load. Once sliding begins, the coefficient of friction generally drops to the a new value,  $\mu_D$ , called the coefficient of dynamic friction [115]. Homola et al. [116] and Berman et al. [117] showed that the sliding friction for adhering, smooth, flat surfaces is more accurately represented by the following governing equation:

$$T = \tau_0 A + \mu_D N \tag{1.5}$$

where A is the contact area and  $\tau_0$  is the critical shear strength, a material property similar to the coefficient of friction or the interfacial adhesive strength.

#### Theory and experimental results of structured interfaces in shear

Although the models presented above have been confirmed for stiff unstructured surfaces, equation (4) has been used to help understand the behavior of soft fibrillar interfaces by Majidi et al. [16], Kim et al. [19], Aksak et al. [118], Tian et al. [119] and Varenberg and Gorb [120] among others. This model seems appropriate when considering the fibrillar interface at the macroscale, but it fails to explain the behavior of individual fibers. Buckling of individual fibers appears to play an important role in the friction of arrays of soft microstructures as observed in the difference between experiments carried out by Kim et al. [19] and Varenberg et al. [120]. For Kim, structured surfaces exhibited greater friction performance than the unstructured control, but Varenberg observed the opposite effect. Kumar and Hui show through numerical modeling that these contradictory results are explained by the manner in which the tests were carried out: Kim conducted shear tests with a constant displacement boundary condition, whereas Varenberg had constant normal load leading to buckling of the fibers [121].

Gravish et al. experimentally characterized the gecko's frictional performance and found that there is no drop in performance when sliding begins, and, in fact, the friction of the gecko adhesive pad increases with increasing rate of shearing [122]. To help explain this, they propose a model of stick-slip that treats the fibers as vibrating beams that intermittently bond with a surface before detaching and re-bonding again. This model seems relevant for stiff fibers with appreciable tip contact, but as we will see, this is not what is found in the literature of synthetic structured adhesives.

The theory of the frictional behavior of structured adhesives currently lags behind experimental results. Significant interest in structured friction has shown us that stiff and soft structured surfaces have conflicting results regarding enhancement through surface

structuring. Stiff microstructures made of materials with elastic moduli on the order of gigapascals tend to have larger aspect ratios, and hence make contact along the sides when sheared across a surface. These arrays of long stiff fibrils exhibit greater coefficients of friction than the unstructured control surfaces made of the same stiff material [16, 123, 124, 125, 126, 127, 128, 129, 130, 131]

Soft microstructure arrays with elastic moduli in the order of megapascals are less frequently tested as a friction enhancing surface because of limited durability [9, 19, 77, 120], but the benefit of soft microstructures is in the considerable enhancements to both adhesion and friction. The mechanical principle for enhanced adhesion in soft structures is based on the adhesion of the tips of pillars to the contact substrate. Enhanced friction is closely coupled with enhanced adhesion, and even the anisotropic friction of the structures demonstrated by Murphy et al. clearly show that the "gripping" and "releasing" cases are defined by whether the tips or the edges are in contact with the substrate [9].

# **1.4 Gecko-Inspired Adhesives and their Fabrication**

As we have seen from the previous work done in the field of gecko adhesives, there are many important parameters for making strong structured adhesives, and even more parameters to enable the secondary behaviors of controllability, directionality, and self-cleaning. To date, there is no single demonstrated synthetic gecko adhesive that matches the seven specifications of the real gecko as formalized by Autumn that we presented in section 2.3. Even so, there is a significant body of work that demonstrates several of the gecko properties in synthetic analogs, and here we present a wide variety of these synthetics (see Figure 1.4) and the means of their fabrication (see Figure 1.5 for fabrication strategies of hierarchical structures).

# **1.4.1** Macro- and Microscale Fibers

After initial studies revealed the billons of nanoscale fibers on geckos' feet and that adhesion of these structures was essentially universal thanks to van der Waals forces [7, 37, 38],



Figure 1.4: (a) Vertical nanopillars created by oxygen plasma etching of polyimide. (Reprinted with permission [13]. Copyright 2003, Nature Publishing Group.) (b) Polymer micropillars formed by casting into a micromachined negative template. (Reprinted with permission [14]. Copyright 2007, the Royal Society.) (c) Wedge shaped polymer microstructures cast from a negative photolithography template. (Reprinted with permission [15]. Copyright 2009, the Royal Society.) (d) Polypropylene nanofibers molded and etched free from a commercially available polycarbonate filter. (Reprinted with permission [16]. Copyright 2006, American Physical Society.) (e) Micropillars with triangular cross-sections were cast from dry etched silicon wafers. (Reprinted with permission [17]. Copyright 2011, Wiley.) (f) Hierarchical nanopillars formed through capillary force assisted lithography. (Reprinted with permission [5]. Copyright 2009, National Academy of Sciences.) (g) Hierarchical micropillars produced through a single step casting of polymer to a multiple-level photolightography template. (Reprinted with permission [18]. Copyright 2009, Wiley.) (h) Micropillars with mushroom tips cast from a dry etched silicon-on-insulator wafer template. (Reprinted with permission [19]. Copyright 2007, American Institute of Physics.) (i) Angled micropillars were formed from angled-light photolithography, and the angled mushroom tips were formed from a subsequent dipping into liquid polyurethane. (Reprinted with permission [9]. Copyright 2009, Wiley.) (j) Dipping micropillars into liquid polymer created the round tips in the left image, and subsequently pressing and shearing them against a clean substrate created the offset spatula tips in the right image. (Reprinted with permission [20]. Copyright 2007, Wiley)

researchers sought to create adhesive structures that closely mimicked the size and structure of the gecko's setae. Sitti and Fearing demonstrated that an AFM tip could be used to create nano-imprints into wax from which positive polydimethylsiloxane (PDMS) nanobumps could be molded [132]. However, researchers have focused more on microscale fiber arrays, since the principle theories of enhanced adhesion of the gecko are applicable at larger length scales and the fabrication is significantly easier. A common approach for fabricating microfibers has been to cast polymer to negative templates created through photolithography of SU-8 [4, 9, 15, 20, 77, 86, 100, 101, 102, 106, 118, 133, 134, 135] or deep reactive ion etching of silicon [5, 70, 136]. Rapid prototyping tools, such as such deposition manufacturing, have proven useful for creating macroscale fibers [137], and were paired with microscale fibers to exploit the benefits of hierarchy [9]. Through these works, it has become evident that it is not sufficient to fabricate arrays of simple cylindrical micropillars microstructures, and that to capture the principles of gecko adhesion, further techniques need to be utilized to match the full capabilities of a gecko's foot.

### **Modifications leading to Adhesion Control**

Control of adhesion is becoming an important research focus for synthetic gecko adhesives, and in some respects is as defining a quality as the absolute gains in adhesion through structuring. In fact, one might claim that of the seven principles of gecko adhesives, five are directly or indirectly related to the control of the attachment strength of arrays of fibers. More specifically, by controlling the adhesion of a gecko-inspired material, you might achieve the following properties: get a high attachment force for a minimal preload (Figure 1.2b), reduce the attachment force nearly to zero for easy detachment (Figure 1.2c), attach strongly only if dragged along a surface in a specific direction (Figure 1.2d), prevent unintended stickiness (Figure 1.2e) and clean the adhesive of contaminating particles through normal use (Figure 1.2g).

Angled fibers and tip modification are important factors in controlling attachment strength and have been considered in sufficient detail by the community to get independent treatments below. However, it is important to note other approaches that lead to control of gecko-inspired adhesives. One significant approach is to cast shape memory polymer

(SMP) to create arrays of thermally-responsive synthetic gecko adhesives. Kim et al. created a negative template in silicon through DRIE to cast a SMP micropillar array which demonstrated that pull-off forces could be repeatedly changed by a factor of 4 based on thermal inputs [138]. Reddy et al. purchased silicon wafers with positive fiber templates formed through DRIE to which they cast SMP which demonstrated a 200-fold change in pull-off forces, but only through one heating cycle [139].

In addition to using active polymer materials, adhesion control can be achieved with anisotropy in material properties or fiber geometry. By fabricating triangle tipped pillars, Kwak et al. [17] demonstrated reduction of pull-off force of the adhesive array when sheared in the direction of the vertex of the triangle tips. The triangle tip and cross-section was formed through a combined photolithography and DRIE process. To create anisotropy of material properties of PDMS, Jeong et al. [140] prestrained arrays of micropillars and exposed them to oxygen plasma, which resulted in waves in the backing layer preventing contact of the pillars to the opposing substrate. Subsequent tensing of the backing layer straightened out the waves and allowed the tips of the microfibers to make contact.

#### **Angled Fibers**

Biological studies revealed the importance of asymmetry in the gecko setae for the easy attachment and detachment exhibited during climbing up walls. Engineers attempted to derive analogous behavior in by creating arrays of angled fibers which exhibit anisotropic adhesion and friction. To that end, several methods to achieve this have been implemented, but the most common is to modify the traditional photolithography approach by exposing the photoresist with angled light [9, 15, 25, 77, 118, 134, 141, 142].

Aksak et al. [118] and Murphy et al. [77] demonstrated a series of angled fibers fabricated through angled photolithography of SU-8 photoresist applied to glass wafers. The photolithography process already allowed for control of height and diameter of the microstructures, but angled exposure of the photoresist allowed for the additional control of the angle of the final structures, with angles limited by the refractive index of the SU-8 to around 50° from vertical [9, 77, 118]. Carlson et al. [142] and Mengüçet al. [25] used shear displacement of angled pillars when in contact with a micro-part to reduce the attachment strength and enable reliable release of the part to a receiver substrate. This approach opens

the door to gecko-inspired adhesives to be used as micromanipulators of microchips and other fragile micron-scale devices. Santos et al., Parness et al. and Soto et al. used an angled back-side exposure combined with a more traditional vertical front-side exposure of SU-8 to create a negative template of angled wedges [15, 134, 141]. These wedge shaped microstructures closely mimicked the gecko's frictional adhesion properties, leading to a high adhesion to preload force ratio, low detachment force and anisotropic attachment.

To accomplish the same goal of controlled frictional adhesion, Jeong et al. used angled deep reactive ion etching (DRIE) to create negative templates of angled structures directly into silicon [5]. Normally, during ion etching the plasma ions follow the electric field lines into the silicon substrate at a perpendicular angle, so angling the silicon substrate will not create angled etching because the field lines are still perpendicular. However, by introducing a Faraday cage around the substrate, the perpendicular field lines are eliminated, allowing the ions to strike the substrate at an angle. Combined with capillary force lithography, Jeong et al. created arrays of angled nanofibers with spatula tips and demonstrated the manipulation of a pane of glass for LCD displays [5].

In addition to fabricating mold templates with angled structures, traditional vertical arrays of pillars can be angled through post-casting and post-curing processes. These post-processing steps can generally be divided into approaches that deform structures through stresses internal to the fibers themselves and those that introduce stresses to the surface of the fibers. Internal stresses are introduced through thermal-mechanical processes which use heat and pressure, whereas external stresses are introduced through deposition of a layer of foreign material or irradiation of the surface layer of the fiber material.

Demonstrated external-stress post-processing of adhesive structures include the use of oblique metal deposition [143] and electron beam irradiation [144]. Yoon et al. showed that depositing a sufficiently thick layer (>15 nm) of metal on one side of fibers can bend them either towards or away from the metal face depending on the residual stresses in the metal layer. For thin layers of metal, an additional thermal annealing step induced bending due to the difference in coefficients of thermal expansion in the fiber and thin film materials [143]. Lee et al. showed that electron beam (e-beam) irradiation had a similar effect because it chemically modified a thin layer of polymer on one side of the fibers, causing the fiber to bend in the direction of the source [144]. Kim et al. [145] expanded the technique

to nano-scale fibers, and used oblique e-beam irradiation of polyurethane acrylate (PUA) nanofibers to cause a shrinking in the polymer matrix on the side exposed to the electron beam, resulting in an array of angled nanofibers.

Internal-stress post-processing has been used to angle nano-scale stiff fibers [144] as well as softer micro-scale pillars [139]. To create angled nanofibers, Lee et al. first fabricated vertical fibers by casting thermoplastic polypropylene in a polycarbonate filter at high temperature and under vacuum, then took the vertical fibers and heated them past the glass transition temperature of the thermoplastic and applied pressure with a roller [144]. Reddy et al. [139] demonstrated a method of creating arrays of angled micropillars by first casting shape memory polymer (SMP) to a vertical pillar mold, then loading the cured SMP pillar array in shear while simultaneously being heated past its glass transition temperature.

# **Tip Modifications**

As mentioned earlier, theoretical investigations on the effect of tip geometries suggest that mushroom shaped tips should offer the highest attachment strengths [75], which is also supported by the presence of the flat spatulae at the tips of gecko setae [2]. Researchers have followed this advice in fabricating mushroom shaped tips on synthetic gecko adhesives [9, 14, 70, 76, 77, 78, 79]. The most common procedure for fabricating micropillars with tip modifications is through dipping cured, solid polymer structures into uncured, liquid polymer so the tips are wetted, then letting the newly added polymer cure against a clean substrate. In addition to mushroom shaped tips, by using this dipping method, researchers have created concave tip surfaces [76, 77], offset mushroom tips [76], hemispherical tips [76, 77], and angled mushroom tips [9].

Deep reactive ion etching (DRIE) can be used to create negative molds in silicon for subsequent polymer casting. Additionally, by modifying the etching parameters to exploit the "champagne glass" effect that occurs when the isotropic etching of silicon is inhibited by a layer of unetched silicon oxide, a mushroom shaped tip can be created in the mold template. Kim et al. first demonstrated this approach to create negative templates in silicon-on-insulator (SOI) wafers [70]. Jeong et al. used a similar approach to create the silicon negative mold, but avoided destroying the mold by casting a UV curable polymer through capillary force lithography [5].

In addition to physical modifications to the tips of pillars, the surface chemistry of pillar tips has also been manipulated to enhance adhesion. Sitti et al. [146] showed that the addition of dangling chain elastomers to the tips of PDMS microfibers lead to an almost factor of two increase in pull-off force over non-modified PDMS microfibers. In a combining biologically-inspired engineering approaches, Lee et al. [99] and Glass et al. [100, 101] applied mussel-inspired polymer coatings to gecko-inspired micropillars to increase adhesion under water. Glass et al. showed an almost three-fold increase in the pull-off force of polyurethane mushroom-tipped pillars with mussel-inspired polymer applied to the surface over unmodified mushroom-tipped pillars [101].

# **1.4.2** Nanoscale Fibers

Microscale templates can be created relatively easily with established photolithography protocols, but to create nanoscale templates, engineers have looked to creatively repurpose several other approaches. Jin et al. created an array of polystyrene nanofibers by casting to a commercially available alumina membrane and demonstrated superhydrophobicity and high adhesion to droplets of water, but no dry adhesion to a solid surface [147]. Kustandi et al. and Ho et al. expanded on this approach to create hierarchical structures [148, 149]. In a similar approach, Majidi et al. [150] and Lee et al. [144] took commercially available polycarbonate filters normally used for air or cell monitoring and repurposed them as negative templates to cast polypropolyne. After casting their polymer, the filter was etched away, leaving fibers with nanoscale diameters and microscale lengths [144, 150]. Using filters as negative templates results in stochastically distributed fibers, but Jeong et al. showed that a deterministically arranged array of polyurethane acrylate fibers could be cast by capillary force lithography from a silicon substrate etched using DRIE [5].

Although we are primarily concerned with polymer fibers in this review, it is worth noting the use of carbon nanotubes (CNT) as nanoscale fibrillar adhesives. Arrays of vertically aligned, multi-walled CNTs have been demonstrated as possessing adhesive and shear pressures many times that of the gecko, as well as directionality of friction, and lotus-leaf-like self-cleaning [13, 123, 125, 127, 151, 152]. However, in all cases of testing CNT arrays, the contact substrate was rigid and very smooth due to the limited compliance of the CNTS. In an attempt to address this limitation, Aksak et al. partially embedded arrays of CNTS in a polymer backing to add compliance and improve the robustness of the adhesive, but did not observe any significant adhesion [153].

# **1.4.3** Hierarchical Fibers

It can be argued that the hierarchy of ever smaller structures stacked one on top another is what makes the gecko's foot sticky [3]. The combination of different length scale structures allows for compliance, and hence contact, to a wide range of surface roughnesses from atomically smooth glass to visibly rough rock faces. For this reason, hierarchy is a critical component for gecko-inspired adhesives to be useful in a variety of applications. To that end, fabrication of hierarchical fiber arrays has been achieved through several approaches, which we loosely group into the four categories suggested by Kwak et al. [21]: (1) Multiple mold-casting, (2) Single mold-casting, (3) Thermal imprinting/embossing, (4) Capillary force lithography (see Figure 1.5).

Multiple mold-casting (called dip transfer method by Kwak et al. in their review [21]) is based on the process of casting soft arrays to increasingly finer molds by dipping the tips of the cured polymer fibers to uncured polymer then pressing to the next smaller array mold. Using the multiple mold-casting approach, Murphy et al. [4] were the first to demonstrate a three-level hierarchical pillar array, with the structures ranging down in size from 400  $\mu$ m in diameter at the first level, to 50  $\mu$ m diameter of the second level pillars, to 3  $\mu$ m in diameter of the third level pillars. Limited yield during fabrication of the third level led to only the two-level hierarchical array being tested in adhesion, but the two-level pillars (see Figure 1.1d) demonstrated increased adhesive forces and significantly enhanced interfacial work of adhesion (i.e. energy required to separate two surfaces) over single level pillars. The adhesive force and effective work of adhesion enhancements were about 10% and 50%, respectively, and was largely thanks to the increased compliance of the hierarchical structures.

Single mold-casting, as the name suggests, is similar to multiple mold casting but requires only one step where polymer is cured in a mold. However, the mold for single mold-casting requires all the levels of hierarchy to be incorporating before polymer curing,



Advanced Top-down Fabrication for Hierarchical Structures

Figure 1.5: This figure is an outline of the four schemes for creating hierarchical gecko-inspired adhesives. Reproduced with permission. (Reprinted with permission [21]. Copyright 2011, Wiley.)

which leads to more complex mold fabrication. This is in contract to multiple mold-casting where the molds are simple but the polymer casting/curing process is complicated. Greiner et al. presented a mold used for one-step casting, where the mold was fabricated by a two-step photoresist exposure [18]. The demonstrated hierarchical structures had base pillars that were 50  $\mu$ m in diameter and 200  $\mu$ m tall and second level pillars that were 10  $\mu$ m in diameter and 10  $\mu$ m tall. Unfortunately, the limited area fraction reduced contact area significantly and the hierarchical array had an order of magnitude reduction in adhesive force when compared to the single base level array.

Thermal imprinting/embossing uses a hot melt process instead of a liquid curable polymer to fill the cavities of a negative mold. Generally, melt materials are stiffer than polymers which allows for smaller, higher aspect ratio fibers that more closely resemble the morphology of gecko setae. Kustandi et al. and Ho et al. presented one unique approach to form the hierarchical negative mold by creating an anodic alumina template with branching pores [148, 149]. Subsequently, melted polycarbonate (Lexan) was pressed to the template and peeled off after cooling to create 280 nm diameter base layer pillars that branched into 90 nm diameter top layer pillars. These structures are the closest in appearance and material stiffness to gecko setae thus far produced and presented in the literature. The branching of the tips of the nanopillars increased shear adhesion force by 150% over non-branched single level nanopillars. However, the second-level branched structures deform plastically with just nine loading cycles, which leads to a question of long term durability [131].

Capillary force lithography was first presented as a method for fabricating hierarchical structures by Jeong et al. [5]. Combining capillary force lithography with specially etched angled nano-cavities, Jeong et al. created an array of hierarchical fibers. The base pillars were 5  $\mu$ m in diameter and 25  $\mu$ m in height, and the second level pillars were 500 nm in diameter and 2  $\mu$ m in height. Whereas the base pillars were vertically aligned, the nano-pillars on top were angled, which enabled control of peel-off forces with a ratio of about 10 to 1. More interestingly, the hierarchical fiber array enhanced the attachment to a deterministically "rough" surface (a lattice structure) over the single level array, for sufficiently high roughnesses.

# **1.5** Applications of Bio-Inspired Adhesives

# **1.5.1 Robotics**

What is most exciting about the development of structured adhesives is the range of new of engineering applications. Here we briefly introduce three major applications that have gotten significant exposure in the literature. Robotics can benefit from the structured surfaces because they have a certain amount of passive intelligence, as an illustrative example consider a planar grasper that utilizes a gecko-inspired adhesive surface to pick up panes of glass (see Figure 1.7) [5]. In this example, a traditional grasper utilizing suction would have required an additional vacuum pump and would only have worked on a smooth surface, but the gecko adhesive grasper uses only the actuation already present and can work on rough surfaces. More interesting than this example are applications that would not have even been possible without gecko adhesives, such as tiny, energy efficient, wall-climbing robots. The application that might emerge with the greatest impact is in medical devices, where gecko-adhesives can improve how devices interface with the human body.

# **Mobile Robots**

Mobile robots, and specifically, climbing robots, seem like a perfect application of structured adhesives since the original inspiration comes from examples of natural climbers. The literature bears out this intuition because of the proliferation of climbing robots using gecko adhesives [22, 141, 154, 155, 156, 157, 158, 159]. Sitti uses mushroom tipped structured adhesives that behave more like conventional pressure sensitive adhesives in robots with minimal actuation and a more abstracted morphology (see Figure 1.6a) [22, 154, 155, 156, 157]. Cutkosky et al. has taken the approach of using wedge-shaped structured adhesives that mimic the frictional adhesion of gecko pads and apply them to a highly actuated robotic climber that closely resembles the morphology of an actual gecko (see Figure 1.6b) [141, 158, 159].



Figure 1.6: (a) Waalbot [22] and (b) Stickybot [23] are two robots utilizing gecko-inspired adhesives to climb walls quietly and efficiently. (Waalbot - Reprinted with permission [22]. Copyright 2010, SAGE Publications.) (Stickybot - Reprinted with permission [23]. Copyright 2007, IEEE.)

# Manipulators

Robotic manipulation through the use of gecko adhesives is another obvious application of the technology. Using gecko adhesives as a grasper is so intuitive that mischievous children skip the whole process of designing and fabrication of synthetic gecko adhesives and use the geckos themselves tied to strings as the means for stealing hats off the heads of passing pedestrians [160]. However, the method of grasping using structured adhesives is not as intuitive as this example makes it seem. Jeong et al. [5] use the frictional adhesion behavior of angled nanofibers to manipulate large glass panels used for thin film transistor liquid crystal displays (TFT-LCD). Their manipulation mechanism was enabled by and limited to the shearing loads required for attachment strength, and demonstrated a pick-to-release peel force ratio of 6 to 1. The manipulator was simple in its control architecture because it only needed two degrees of freedom (DOF) to enable and disable attachment, and both DOF where redundant with the three DOF already required for moving the manipulator in three-dimensional space. The Jeong et al. nanofiber array based manipulator was effective in manipulating large planar objects, but could only carry them in the orientation that kept the fibers in shear (Figure 1.7c).



Figure 1.7: (a) The top two images show the deformed state of the square cross-section micropillar in contact with a silicon microplatelet part, and the lower image shows an assembly created with the Kim et al. micromanipulator. (Reprinted with permission [24]. Copyright 2010, National Academy of Sciences.) (b) The image to the left shows an array of angled micropillars, of which a single one is isolated to create the Mengüçet al. micromanipulator seen in the right image attached to a silicon miroplatelet part. (Reprinted with permission [25]. Copyright 2011, Wiley.) (c) Jeong et al. demonstrated an adhesive patch composed of an array of angled nanopillars that could be engaged in shear (left schematic images) to transport LCD glass panels (right two photographs). (Reprinted with permission [5]. Copyright 2009, National Academy of Sciences.)

Kim et al. [24] demonstrated a microscale manipulator with a pick-to-release attachment force ratio of 1000 to 1. The micromanipulator was used to pick up platelet-like silicon microparts from a wafer where they had been fabricated through a monolithic photolithography process and transfer them to a variety of receiver substrates. The reduction of attachment strength was significant enough to deposit the silicon platelets on top of one another, creating three dimensional assemblies and a novel transistor design (Figure 1.7a).

In a recent work by Mengüçet al. [25], the use of an angled elastomer micropillar with either a round or flat tip for pick-and-place manipulation was demonstrated (Figure 1.7b). Utilizing vertical or shear displacement, area of contact between the micropillar and part was selectively modified and hence the attachment strength could be controlled. The pick-to-release attachment force ratio was maximized by utilizing a flat tip micropillar with shear displacement control; the maximum ratio of forces was 39 to 1. Unlike the Kim et al. manipulator, the Mengüçet al. manipulator has a larger contact area when holding the part than when it releases it. This makes it more suitable for larger or heavier parts, and this fact was demonstrated by scaling up the manipulator to an array of micropillars in order to pick-and-place a centimeter-scale glass cover slip.

In a similar investigation, Carlson et al. [142] showed that the application of shear displacement to a modified version of the Kim et al. [24] manipulator could also be used as a method for reducing attachment strength. This approach has the benefit of increasing the holding strength of the manipulator, but at the cost of reduced pick-to-release ratio.

# **1.5.2 Medical Devices**

Kwak et al. [10] studied how structured adhesives could be applied to medical skin patches. The adhesives they fabricated were mushroom tipped vertical pillars made of PDMS (Figure 1.7). They found that when compared to conventional acrylic adhesive patches, their structured PDMS patches had lower adhesion initially, but could be cleaned with water and Scotch tape where the conventional patches could not. This ability to be cleaned allowed the structured adhesive to regain its attachment strength, a significant improvement from traditional adhesives. However, as Karp and Langer [113] pointed out in their review of gecko-inspiration in medical adhesives, the Kwak et al. adhesive only provided 40% of the

attachment strength of traditional adhesives. There is significant room for improvement in this area, and the investigation of structured adhesives on soft substrates like skin is just now beginning.



Figure 1.8: Gecko inspired adhesives can be used as an enhanced medical bandage. As opposed to (a) conventional adhesives, (b) gecko-inspired polymer adhesives allow for air flow to the skin and peel away more easily, resulting in less irritation. (Reprinted with permission [10]. Copyright 2011, Wiley)

Mahdavi et al. [111] took a different approach for gecko-inspired adhesives, and instead of applying them externally, they implemented them internally as possible sutures. Using arrays of tapered pillar structures with a bio-adhesive coating (dextran aldehyde, DXTA), they showed that they could improve shear adhesion two-fold over a flat unstructured control without bio-adhesive coating. Additionally, they fabricated the adhesives from a biodegradable, biocompatible elastomer that ensured the suture would not inflame the contacted tissue and that it would be dissolved by the body over time. The geckoinspired adhesive was only tested in shear and showed the surprising property of increased shear adhesion for reduced structural density, which goes counter to the contact splitting principles reviewed earlier. Mahdavi et al. claim that this unexpected result is due to the structured adhesive contacting a relatively soft tissue substrate, a condition that has not yet been carefully considered.

Another proposed medical device that utilizes gecko-inspired adhesives is an active endoscopic capsule presented by Cheung et al. [161] and improved by Glass et al. [162]. By utilizing legs that can be actively extended and retracted from the capsule body and by applying gecko-inspired adhesive on the legs, the capsule could apply sufficient attachment force to the walls of an esophagus in vitro to withstand the peristaltic forces that would be expected in vivo.

# **1.6 Research Objectives**

The core of this thesis work is to expand the understanding of the principles of controllable adhesion and apply this understanding to the task of micromanipulation and to the development of self cleaning microstructured adhesives. These objectives will be accomplished through an iterative process of characterizing structural adhesion, modeling of the mechanical principles, confirming the modeling results through further characterization, and developing new structures which are optimized based upon the model's suggestions. The following are the main research objectives of this thesis:

- To characterize the underlying principles of controlled adhesion through the use of microstructured surfaces. This is done by characterizing the mechanical behavior and adhesion of fibers with different geometries under different loading conditions.
- To develop models in order to suggest optimal geometries of structures and optimal loading conditions. The models will apply an understanding of both static loading of beams and soft bodies and the dynamic energy release and restoring behaviors. Charicterization of mechanics and adhesion will inform the model design. Results from models will in turn suggest optimal structural geometries and loading conditions.
- To apply the understanding of the principles of structural behavior to the micromanipulation of parts. Parts of dimensions ranging from the micrometer scale to the centimeter scale were manipulated through pick and place techniques.
- To implement the design suggestions from modeling and apply the understanding of practical concerns in deterministic micromanipulation to the development of self cleaning structural adhesives. This is a critical limitation in current applications of structural adhesives as a novel commercial product, and this research focus has the potential for immediate and wide ranging contributions.

# **1.7 Contributions**

The major contributions of this thesis work revolve around the understanding of the principles of controllable adhesion of microstructured surfaces and its applications. The applications in micromanipulation and self cleaning adhesive surfaces will have the possibility for immediate impact in industry and other research fields. Understanding the principles of microstructured adhesion will also have the scientific benefit of describing in greater detail how the biological examples seen on the feet of geckos and other climbing animals function. The field of microstructure adhesion is rapidly maturing, but still requires significant contributions before it becomes a source of good for society. This work provides the following two core contributions:

- Gecko-inspired adhesives as controllable, safe and universal micromanipulators. We showed that through control strategies involving vertical and shear displacement, the attachment force of a single elastomeric pillar could be reduce almost 40 fold. This adhesion control was then used to demonstrate a micromanipulation system and propose a framework of manipulation.
- 2. Contamination-resistant and self-cleaning microstructured adhesives. We showed that self-cleaning actually can occur along three different regimes: rolling, depositing, and embedding. All three regimes can restore a large portion of the initial attachment strength of a gecko-inspired adhesive. This finding is significant because it is the first of its kind for synthetic gecko-inspired adhesives, and also because it suggests a direction of inquiry into the cleaning ability of natural gecko adhesives.



# Gecko-Inspired, Controllable Adhesives Applied to Micromanipulation

# 2.1 Introduction

Geckos are one of Nature's most agile and power efficient climbers due to their strong, highly repeatable, high speed, and controllable attachment and detachment capabilities on a wide range of smooth and slightly rough surfaces. Such capabilities are a result of angled and hierarchical micro and nanoscale fibrillar structures on their feet, which have saucer shaped tip endings [37, 38]. These micro/nanostructures can exhibit repeatable adhesive strengths up to 200 kPa [8, 11] on smooth and rigid surfaces such as glass. The attachment strength of gecko foot-hairs was shown to be rooted in intermolecular forces such as van der Waals forces, which exist between all surfaces and is fairly insensitive to surface chemistry [38]. Such generic attachment principle enables the animal climbing on a wide range of surface materials. The importance of geometry, size, material type, and surface physics of these biological foot-hairs rather than their surface chemistry in adhesion strength leads to these biological adhesives to be called *structured adhesives*. Many researchers have been proposing methods to design and fabricate such synthetic micro/nanostructured adhesives inspired by gecko foot-hairs [4, 5, 13, 14, 16, 19, 69, 70, 106, 118, 123, 163, 164].

In addition to high attachment strength, biological micro/nanofibrillar structures exhibit highly controllable adhesion [7, 17, 37, 51, 165, 166, 167]. The controlled adhesion and

shear strength of gecko's angled fibrillar structures is dependent on mechanical deformations induced by vertical and lateral loading of its feet [8, 39], which can actively control the contact area between the structures and the substrate. Autumn et al. [8] demonstrated that gecko foot-hairs have a friction ratio of around 5 to 1 comparing the *with* to *against* hair tilt directions.

Synthetic structured adhesives have attempted to mimic the strength and controllability of these biological foot-hairs. Lee and Fearing showed that when stiff polymer microfiber arrays are angled they exhibit anisotropic behavior of shear strength with a ratio of 45 to 1 between dragging resistance in *with* and *against* fiber tilt directions [130]. However, in both of these vertical and angled cases, the microfibers had low adhesive strength. Zhao et al. [168]. used multi-wall carbon nanotubes (MWCNT) to create a structured surface with even smaller features that exhibit adhesion pressure of 100 kPa and shear strength of 80 kPa, but these MWCNT surfaces lacked controllable adhesion. Similarly, embedding MWCNT arrays in polymer backing showed enhanced friction [153].

In the study with results closest to the strength and controllability of biological foothairs, Murphy et al. [9] developed elastomer, angled polymer fibers with angled mushroom shaped tip endings which demonstrated interfacial shear pressures of 100 kPa and adhesion pressure of 50 kPa. These structures exhibited controlled shear and adhesion strength: *with* and *against* friction ratios of around 5 to 1 and adhesion ratios of 35 to 1. Subsequently, surface treatments have been used to enhance adhesion of polymer microfibers in air [146] and under water [100, 101]. In a different approach to adhesion control, thermal control has been used on shape memory polymer fiber arrays [138].

The aforementioned preload- and shear-controlled adhesion and friction properties could be one of the major reasons why biological gecko foot-hairs can shed dirt particles in dry conditions [11, 24]. Hansen and Autumn [11] demonstrated that dirt microparticles much larger than the fiber tip diameter could be shed from the gecko's foot after it is attached to and detached from a clean glass substrate in many cycles, a process termed *contact self-cleaning*. Such contact self-cleaning property has also been shown in synthetic polymer fiber adhesives [130] by shear loading. These studies suggest that micro/nanos-tructures could also be used for pick-and-place manipulation of micro or macroscale parts

since they enable controlled attachment (pick) and detachment (release). Therefore, microstructured adhesives inspired by these biological structures have recently been used for manipulation at the micro [24, 142] and macroscale [5, 140]. Kim et al. [24] proposed elastomer micropyramidal structures as adhesion controlled micromanipulators. These microstructures used vertical compression induced contact area control such that there was a relatively large contact area when sufficiently large compressive loads buckled the microstructures. If pulled away quickly, the planar part was picked up with a high pull-off force because rate-dependent effects enhanced the adhesion strength further [108]. After the part was picked, the buckled elastic structures reverted to their original shapes. This shape recovery significantly reduced the contact area, and thus, adhesion, between the pyramid structures and the part and enabled easy part release. The maximum ratio of pick to release adhesive forces was 1000 to 1. But, this manipulator had small holding forces after lifting the part from the donor substrate, which could be a problem for heavy parts or for mechanical disturbances during transfer of the parts. Carlson et al. [142] addressed this limitation by removing the micropyramidal structures of the Kim et al. manipulator and used shear displacement control to reduce attachment strength, at the cost of a reduced pick to release force ratio. Jeong et al. [5] utilized angled nanofibers with high shear strength to transfer thin film transistor (TFT) displays under vacuum or air as a macroscale manipulation demonstration. However, micron scale part manipulation was not demonstrated and the nanofiber array required a constant application of shear force for strong adhesion.

In this study, to improve the versatility and simplicity of the elastomer micro/nanostructure based pick-and-place manipulation of macro and microscale parts, we developed a gecko foot-hair inspired angled pillar microstructure with flat or round tip ending shape (Figure 2.1). We present two simple control methods for reducing attachment strength of the pillar during the part release: vertical displacement control and shear displacement control. Picking of the part is accomplished in the same way for both control methods, by vertical compression of the tip to the part and rapid retraction to maximize adhesion strength. During transfer of the part, the attachment between the pillar and the part is secure enough to withstand sudden impacts and disturbances as well as the weight of the part, issues that could be a limiting factor with the previously demonstrated manipulator from Kim et al. [24]. During release of the part onto a receiver substrate, the contact area of the pillar to the part is drastically reduced by the deformation of the pillar due to either the vertical or shear displacement control method. As a difference from the nanofiber arrays demonstrated by Jeong et al [5], the parts can be picked and released in both adhesion and shear modes for the approach presented here. Such compliant micromanipulators are simple and inexpensive to manufacture, easy to integrate into optical microscopy infrastructure, and can operate in air, in vacuum and under liquid. Finally, such compliant polymer micropillars are safe for use with fragile parts, and, due to exploiting intermolecular forces, are effective on most materials. This micromanipulation system's ease and effectiveness will be a benefit to the assembly and packaging of microelectromechanical systems and optoelectronic and flexible electronic devices.



Figure 2.1: Scanning electron micrographs taken from an isometric viewpoint of (a) the round tip micropillar, (b) the flat tip micropillar, and (c) side view of the flat tip pillar attached to a silicon platelet part. The micropillars are made of elastometric polyurethane. The white scale bars represent  $50 \,\mu\text{m}$  of length.

# 2.2 Experimental Methodology

# 2.2.1 Fabrication

Previous work has shown the importance of the tip geometry on the adhesion and friction of microfiber adhesives [70, 76, 77, 79, 134]. To investigate the importance of tip geometry in our proposed micropillars, we used two distinct pillar types that were similar in all geometric and material parameters except for the shape of the tip. The first type has a flat tip, the surface of which is parallel to the plane of the backing layer. The second type's

tip is in the shape of a rounded bump with a given curvature. The principle of our fabrication methodology is based on an optical lithography based microstructure fabrication [169] followed by a molding based replication [163]. Angled elastomer micropillars can be fabricated by replicating positive pillars fabricated by directional reactive ion etching [5] or SU-8 lithography [118]. The latter method is selected in this study due to its simplicity (see Appendix C for details on SU-8 photolithography).

Flat tips were formed from negative SU-8 molds because the polymer tips cure against the atomically smooth silicon wafer (Figure 2.3a). The angled flat tip micropillar fabrication process started with the patterning of an SU-8 mold. A silicon wafer was spin coated with a 160 nm thick anti-reflection layer (XHRiC-16, Brewer Science). On top of the anti-reflection layer, SU-8 negative photoresist (SU-8 50, Microchem) was spin coated and soft-baked into a 90 µm thick layer. To fabricate the angled pattern, the wafer with soft-baked SU-8 was mounted on an angled stage and exposed to ultraviolet (UV) light, followed by a post-exposure baking and development. The resulting SU-8 mold was a negative pattern, i.e. composed of angled holes (Figure 2.3a), which were hard baked at 180 °C for 3 min to induce further crosslinking. To facilitate the delamination of poly-dimethylsiloxane (PDMS) from the SU-8 (Figure 2.2b), the mold was exposed to the vapor of tridecafluoro-1,1,2,2-tetrahydrooctyl-1-trichlorosilane for 60 min in a dessicator.

Rounded tips are formed from positive SU-8 molds because the tips of the standing SU-8 posts are etched more along the perimeter creating a curving of the top surface (Figure 2.3f). By tuning the exposure and development times, the curvature can be controlled. The angled round tip micropillar used in this work was fabricated using the SU-8 lithography and molding techniques described in previous works [118]. In a similar approach to the flat tip pillar fabrication, SU-8 photoresist (SU-8 2050, Microchem Corp.) was spun on a fused silica wafer and exposed through a mask by angled UV light (MA-56, Karl Suss). The difference in round-tip fabrication from flat-tip fabrication was in the mold, the round-tip mold is a positive pattern, i.e. composed of angled pillars (Figure 2.3f). The SU-8 pillars were then molded with a silicone rubber (HS II RTV, Dow Corning) which served as the negative pattern mold for creating arrays of elastomer micropillars (Figure 2.3h). The curvature of the round tip structure was characterized with interferometric profilometry and the radius of curvature was found to be 380 µm (Figure 2.5).

# 2.2.2 Detailed Fabrication Methodology

The fabrication process allowed for the selection of a desired geometry of a single angled micropillar from the stochastic distribution within an array of structures. Following previous photolithography and molding techniques, a negative rubber mold was created (Figure 2.2a-d). The polyurethane positive array was cured with a glass substrate backing which acted as a handling layer (Figure 2.2e). A silicon platelet part was adhered to the desired micropillar to act as a cap to protect the tip surface (Figure 2.2f). The UV microlaser milling isolated the micropillar (Figure 2.2g). After releasing the platelet cap (Figure 2.2h), the surrounding structures and backing layer were manually removed with the tip of a sharp blade (Figure 2.2i). The soft lithography steps were repeated with the isolated structure (Figure 2.2j-m). Only a few of the final single structures were molded, but no variations were observed through optical microscopy. However, if this approach is to be used for industrial purposes, a more rigorous analysis of reproducibility will be required.

The SU-8 was from MicroChem, the silicone mold making rubber was HS-II from Dow Corning, the PDMS was Sylgard 184 from Dow Corning, and the polyurethane was ST-1087 from BJB Enterprises.

Photolithography of SU-8 using a UV light source is a relatively accessible and established process, but it is not the only approach to producing angled polymer micro/nanostructures. Jeong et al. [5] adapted the process of deep reactive ion etching (DRIE) to the angled etching of polysilicon. This allows for a higher degree of control and repeatability in the structures' geometry, but requires a less common fabrication technology. Conversely, we addressed the issues of consistency in SU-8 fabrication by identifying and isolating single structures with desired geometries (Figures 2.2e-i).

The material used as the final micropillar structures was ST-1087 (BJB Enterprises, Inc.), a polyurethane elastomer with a Young modulus of 9.8 MPa and a work of adhesion to glass of 32 mJ m<sup>-2</sup> [77]. This particular polyurethane was selected for this study for the same reasons it has been used in previous similar studies: because of its high tensile strength and high surface energy while remaining optically transparent [70, 77, 118]. The geometry of the structures was characterized with optical microscopy (TE200 Eclipse, Nikon), interforemetric profilometry (NewViewTM 7300, Zygo), and scanning electron



### Soft Lithography and Repeatable Array Molding

Figure 2.2: The fabrication process can be roughly grouped into three sub-processes: (a-d) soft lithography and repeatable array molding, (e-i) isolation of a single structure, and (j-m) repeatable molding of the isolated structure. (a) Photolithography produces the initial negative SU-8 mold. (b) PDMS is cured in the negative mold to produce a positive array. (c) Silicone rubber is cured to the PDMS positive to create a soft negative mold. (d) Polyurethane elastomer with a glass backing is cured in the silicone rubber negative. (e) The positive polyurethane array is removed from the mold after curing. (f) A single pillar picks a silicon platelet part to protect the tip surface. (g) A UV ablation laser cuts a perimeter around the selected pillar into the backing layer. (h) The silicon platelet part is released. (i) The surrounding pillar array is scraped away with the tip of a scalpel. (j) What remains is a single pillar on a glass backing. (k) Silicone rubber is used again to create a negative mold of the isolated pillar. (l) Liquid polyurethane with a new glass backing is placed in the negative silicone mold. (m) The single pillar is removed after curing.



Figure 2.3: Schematic representations of the fabrication process. a) Starting with an SU-8 negative mold, b) we could cure the liquid polymer directly, c) to produce the positive micropillar array, and, d) finally select and isolate a single structure. e) Starting with an array of positive SU-8 micropillars, f) we first cured a negative silicone rubber mold, g) then liquid polymer was cured, h) to produce the positive array and i) select and isolate a final structure. Fabricating structures from a negative photoresist mold (a through d) results in angled pillars with *flat* tip endings (see Figure 2.1b). Replicating positive photoresist structures (f through j) results in angled pillars with *round* tips (see Figure 2.1a).

microscopy (SEM, Hitachi 2460N). All structures were molded onto square glass plates,  $\sim 2$  mm on a side, to provide a rigid, transparent backing and to ease manual handling (Figure 2.3d). The molding process resulted in the plate being covered in several hundred pillars, with a polyurethane backing layer less than 20 µm thick between them and the rigid plate. This thin backing layer is advantageous because it reduces any complicating effects of the soft backing [103].

# 2.2.3 Experimental Setup

In order to characterize the performance of the microstructures, a custom experimental system was employed. This system is based upon automated flat-punch indentation setups previously used in adhesion characterization experiments [8, 9, 130, 170]. Using an inverted optical microscope (TE200 Eclipse, Nikon) as the base for the fixturing as well as the source of visual feedback, a vertical axis of motion and sensing was mounted such that the point of intersection between the pillar micromanipulator and substrate would occur at the focal range of the optics (Figure 2.4). The vertical axis motion was provided by a linear motorized stage (MFA-CC, Newport) with submicron positional accuracy and a speed

range from  $1 \ \mu m s^{-1}$  to 2500  $\mu m s^{-1}$ . The vertical stage was mounted to a two axis manual linear stage (462 Series, Newport) and a two axis goniometer (GON40-U, Newport) to align the adhesive sample with the optics and the substrate.



Figure 2.4: Photograph, (a), and schematic, (b), of the micromanipulation system: A - load cell, B - micropillar sample, C - substrate, D - microscope objective, E - two axis manual linear stage, F - two axis manual goniometer, G - motorized linear stage, H - light source.

Sensing was achieved through a high resolution load cell (GSO-10 and GSO-30, Transducer Techniques), which was used with a signal conditioner (TMO-2, Transducer Techniques). The video was captured through a color digital camera (DFW-X710, Sony) connected to a desktop computer (Aspire ASE380-ED500U, Acer) operating Linux (Ubuntu 7.10 Gutsy Gibbon). The force data was captured as an analog voltage signal through a data acquisition board (NI PCI-6259, National Instruments) mounted in the computer, and all motion control was achieved through commands sent from the computer to a motor controller (ESP300, Newport) to which the motorized stage was connected. All data capture and motion control was managed by custom software running on the computer.

The experimental control parameters included the speed of approach of the adhesive sample to the substrate, the initial amount of compressive load applied (preload), the amount of displacement in the compressive direction after preloading, the amount of displacement in the lateral shear direction after preloading and finally the pull-off speed. The variable which was measured was the applied normal force on the micropillar during loading and retraction. Visual feedback from the video recording gave qualitative information regarding the mechanics of the structures. Contact area visualization was enhanced by interference patterns in 546 nm wavelength green light (see Appendix B for details on the principles of interferometric microscopy).

It is important to note that the control variable in all experiments was displacement, either vertical or shear. Force based control failed to capture intermediate load states because of the unstable nonlinear response of the pillars under compression.

### **Vertical Displacement Experiments**

A typical adhesion characterization experiment would have the structural adhesive sample mounted on the vertical axis such that the adhesive was pointing downward towards the substrate mounted to the microscope fixture. After approaching at  $1 \,\mu m \, s^{-1}$  (the approach speed was constant during tests) and achieving a desired preload of 0.05 mN (constant for all tests) the vertical stage would continue to compress the pillar for a prescribed displacement. Once the prescribed compressive displacement was achieved, the vertical linear stage retracted the micropillar at a constant velocity. The maximum tensile force during pull-off was recorded as the adhesive force.

# **Shear Displacement Experiments**

In the case of applying shear displacement during the part release, the manual linear stage was employed after the compression step was completed, but before retraction. After achieving the prescribed compressive displacement the motorized linear stage paused for 10 seconds to allow the experimenter to displace the pillar laterally through the use of the manual linear stage. As before, the maximum tensile force was recorded as the adhesive force.

# **Demonstration of Pick-and-Place Manipulation**

A micromanipulator composed of a single angled pillar was used for all empirical characterization as well as demonstrations of pick-and-place of  $100 \times 100 \times 3 \ \mu\text{m}^3$  silicon platelets. The silicon parts were fabricated according to the technique presented by Kim et al. [24]. The manipulation of the centimeter-scale glass slide was conducted with an array of 100 round tip pillars arranged in a square packed pattern with 120 µm center to center distance.

# 2.3 Results

# **2.3.1** Characterization of the curvature of the round tip structure

The surface topography of the round tip structure was imaged using a interforemetric profilometry (NewViewTM 7300, Zygo). By taking a cross section of the surface, we could use a circle-fitting algorithm [171] to identify the radius of curvature along that cross section. The shape of the round tip was found to be ellipsoidal, not spherical, but we identified the major axis curvature as  $\sim$ 380 µm and the minor axis curvature as  $\sim$ 90 µm. The results of the analysis can be seen in Figure 2.5.



Figure 2.5: (a) Side view SEM micrograph of the round tip pillar structure. (b) Top view micrograph. (c) Surface topography as imaged by an interforemetric profilometer, with a white dashed line indicating where the cross section is taken. (d) The cross section is indicated with a black dashed line, and the fitted circle is indicated by a blue line.

# 2.3.2 Effect of tip shape

Two micropillar geometries were investigated, one with a flat tip and one with a rounded tip. The flat tip pillar's contact process is captured in micrographs and sketches in Figure 2.6,

where the contact area micrographs show that the "toe" (defined as the edge further away from the base) of the pillar peels up after a critical amount of compressive displacement (Figure 2.6c). A rounded tip pillar's contact process resembles the flat tip process, except for the lack of a critical peeling event, rather, the tip slides along the surface until the entire pillar is bent over and prone. The behavior of these contact processes was captured quantitatively in force versus displacement graphs, Figure 2.7 and Figure 2.8 for round and flat tips, respectively. The graphs show that there is hysteresis in the loading and unloading of the micropillar which influences the pull-off force: by compressively loading the pillar, either rounded tip or flat tip, it first makes good contact resulting in high pull-off forces. Further compression causes the tip surface to either peel away in the case of the flat tip, as indicated by the sharp drop in the measured compressive force seen in Figure 2.8c. The cause for this mechanical instability seems to be related to the nonlinear stress distribution at the tip-substrate contact face (Figure 2.21). In the case of the round tip pillar, the tip slowly slides until the pillar is bent and making contact on its side (Figure 2.7c). By controlling the vertical or shear displacement, we controlled the contact area of the pillar, and thereby control whether it is in the pick state, defined as when the pillar exerts the maximum pull-off force, or in the release state, defined as when the pull-off force is minimized.

Comparing the behavior of the flat tip pillar and round tip pillar under compression shows that the flat tip has a larger pull-off force and a sharper switch between the "pick" and "release" states, which we define as the states where we exert maximum and minimum pull-off forces, respectively (Figure 2.9). The round tip has a less sharp distinction between pick and release states, and a lower peak pull-off force. The pick-to-release adhesive force ratio of the flat tip was found to be 35 to 1 and the round tip had an pick-to-release adhesive force ratio of 26 to 1. It should be noted that the peak pull-off force of the flat tip was twice that of the round tip, but the pick-to-release adhesive force ratio of the flat tip was less than twice that of the round tip pick-to-release adhesive force ratio because the releasestate of the round tip proved to exert a smaller force. It was observed that the release-state depended on the roughness produced through fabrication stochasticity along the edge of the tip, and we hypothesize that deterministically adding bumps or other structures along the edge will reduce the release-state adhesion and enhance the pick-to-release ratio. We observed that alignment was a factor for improving performance of the flat tip, but could


Figure 2.6: Each column shows three corresponding images: (top row) video stills of the flat tip pillar's contact to a smooth, flat glass as seen through an inverted microscope with monochromatic green lighting; (middle row) side view video stills of the profile of the flat tip pillar as it is vertically compressed; (bottom row) side view schematics of the pillar profile during vertical compression and retraction included in order to aid in visualizing the process. The process begins when the tip barely makes contact, (a), before fully contacting the surface, (b). Additional compression causes peeling due to mechanical instability, (c), after which the tip continues to slide along and peel away from the surface, (d,e). Upon retracting, the contact patch is seen to be minimized, (f). The scale bars for each row is included in column (a), and all represent the same length: the diameter of the flat tip,  $35 \,\mu\text{m}$ .



Figure 2.7: Force-distance (FD) curves of the round tip pillar obtained from indenting it onto a glass slide. FD data of the loading, at a constant compression rate of  $1 \ \mu m \ s^{-1}$ , can be seen as the overlapped red lines flowing from left to right. The pillar was retracted at 100  $\ \mu m \ s^{-1}$  after different distances of vertical compression were obtained, which created the separate blue lines flowing from top right to bottom left at different intervals. The schematics of the side view of the micropillar profile are based on optical microscopy observations captured via video and correlated to the empirical FD data; the schematics show the physical behavior at points of interest along the curve, highlighted by call-out boxes. Following the red FD curve from the origin (at the intersection of the dashed lines) to the point of vertical compression at (a) then retracting along the blue curve shows how to obtain a high adhesive force, i.e maximum tensile force, at point (e). The adhesive force is significantly reduced if, beginning from the origin again, you compress the pillar until it is prone, as in point (c), before retracting to point (d), where we see that only edge contact is made at the moment of separation.



Figure 2.8: The flat tip pillar was compressed onto a glass slide at  $1 \ \mu m s^{-1}$  then retracted at  $30 \ \mu m s^{-1}$  to create force-distance (FD) curves. Loading is graphed as overlapping red lines flowing from left to right, and retracting data is graphed as intermittently spaced blue lines flowing from the top-right to the bottom-left. The schematics of the micropillar profile are labeled to correspond directly with the information in Figure 2.6, and the schematics are mapped by call-out boxes to the points along the FD curve where the mircopillar takes the represented shape. Compressing the pillar from the origin (the intersection of dashed lines) to gentle contact at point (a), then to point (b) before retracting to point (b)\* gives a high adhesive force (i.e. maximum tensile force). Note that the shape of the pillar at (b)\* is visually identical to its shape at (b), but it is in tension, so the \* is used to denote the difference. Compressing the pillar past (b) reveals a mechanical instability from point (c) to point (d) where the tip peels away suddenly, and by compressing even further, only the edge remains in contact at point (e) before retracting to point (f) where the pillar is making minimal contact at the moment of separation.

be neglected for the round tip. This difference may lead to a design choice in the future for applications requiring easy or robust alignment. The higher pull-off force and sharper distinction between pick and release states leads us to use the flat tip pillar as the primary manipulator for the remainder of the work.



Figure 2.9: The adhesive forces of flat and round tip pillars measured during pull-off from a glass substrate, after a given vertical displacement in the compressive direction, are plotted for different retraction speeds. The slowest available retraction speed of our actuator,  $1 \ \mu m \ s^{-1}$ , minimized the adhesive forces for both the flat tip pillar (solid red lines connecting filled circles) and the round tip pillar (dashed red lines connecting open circles). The optimal pull-off speed for the flat tip was  $30 \ \mu m \ s^{-1}$  (solid blue lines connecting filled diamonds) and for the round tip the optimal pull-off speed was  $100 \ \mu m \ s^{-1}$  (dashed blue lines connecting open diamonds). Each data point represents the median and the error bars indicate the minimum and maximum force values of three experiments. These results demonstrated how the flat tip pillar has higher maximum ratio of 35 to 1 and sharper switch between pick and release states than the round tip pillar with a maximum ratio of 26 to 1 and a smooth switch between states.

## **2.3.3** Effect of shear displacement

Aksak et al. [118] in a previous investigation into flat tipped angled micropillars, proposed an analytical model of the stress on the tip of the pillar. That model suggests that the angle of inclination of the pillar facilitates an uneven stress distribution during loading, causing the pillar to lose tip contact. We have already shown how we can maximize or minimize adhesive forces simply by loading the pillars compressively (Figure 2.9). However, a similar control strategy can be implemented by the addition of shear displacement. In Figure 2.10, we see that with no shearing and good tip contact, achieved through 4  $\mu$ m compression, there is a maximum pull-off force. Any amount of lateral shear displacement reduces the pull-off force until the release state is achieved for shear displacements of  $\geq 8 \ \mu$ m. In this case, the repeatably observed pick-to-release adhesive force ratio of 39 to 1 is comparable to, but greater than, compression only switching. From micromanipulation trials, we found that using shear displacement control of adhesion to be repeatable and reliable. We found shear displacement control to be more reliable than compression-only control during pick-and-place experiments.

## 2.3.4 Effect of pull-off speed on adhesive force

Investigating the effect of pull-off speed on pull-off force reveals that there is, in fact, a limit to the benefit of increasing speeds. Figure 2.11 shows that retracting at faster and faster speeds from tip contact (4  $\mu$ m compression) can only increase the pull-off force by a factor of 6 before there is a drop off. Interestingly, pulling the pillar away from edge contact (20  $\mu$ m of compressive displacement), at faster and faster speeds actually appears to have a neutral or even a negative effect on the eventual pull-off force. We hypothesize that this is due to different regimes of viscoelasticity: surface viscoelasticity dominates in the case of the pull-off force from tip contact and proves to be beneficial, but bulk viscoelasticity dominates in the case of the highly bent edge contact case and prevents the material from relaxing to make better contact as the pillar is retracted. This difference between surface and bulk viscoelasticity is reviewed by Shull [107]. This graph shows that when in the pick state, the micropillars pull-off force can be increased 6 fold. The release state does not show a strong relation to pull-off speed (Figure 2.11).



Figure 2.10: The adhesive forces of flat tip pillars measured at pull-off for different shear displacements and retraction speeds. Flat tip pillars where first contacted to glass with 4  $\mu$ m of compression to ensure maximum tip contact, then sheared laterally before being retracted vertically at 1  $\mu$ m s<sup>-1</sup> (plotted with red circles), 10  $\mu$ m s<sup>-1</sup> (green squares), or 30  $\mu$ m s<sup>-1</sup> (blue diamonds). Each data point and error bars represent the median and minimum and maximum force values, respectively, of three tests. The maximum pick-to-release adhesive force ratio was found to be 39 to 1.



Figure 2.11: A flat tip micropillar was vertically displaced 4  $\mu$ m to achieve maximum contact area of the tip or 20  $\mu$ m to induce deformation and create edge contact which minimized contact area. Retraction speeds ranged from 1  $\mu$ m s<sup>-1</sup> to 100  $\mu$ m s<sup>-1</sup>. Each data point and error bars represent the median, minimum and maximum force values, respectively, of three tests. There was a strong positive relation between adhesive force and pull-off speed when retraction started from the tip contact condition (curve plotted with a solid green line connecting circles). Retracting from the edge contact condition revealed a weak, slightly negative relation between adhesive force and pull-off speed (curve plotted with a dashed orange line connecting diamonds).

## 2.3.5 Adhesion dependence on preload

The results of adhesion experiments on a single fiber array sample can be seen in Figure 2.12. Both figures must be considered in understanding the attachment behavior of the fiber array. In figure 2.12a, adhesion versus preload is plotted for several retraction velocities and there are three distinct regions represented: (1) the region of high adhesion on the left side, (2) the region of low adhesion on the right side, and (3) the region of instability between high and low adhesion. The error bars at each point of data, which represent the standard deviations for three adhesion measurements with the same preload and retraction velocity, show how there is more variability in the narrow region between high and low adhesion than the regions on either side. This sensitivity is due to the fiber deforming which is discussed below.

In figure 2.12b, the adhesion control ratio is plotted versus retraction velocity. We define the adhesion control ratio as the ratio of the maximum measured adhesion to the minimum measured adhesion for any constant retraction velocity. This ratio is meant to convey the amount of change possible in the attachment strength of a fiber array. The data shows how the controllability ratio changes for different retraction velocities, with a peak occurring at  $30 \,\mu m \, s^{-1}$ , where the ratio is almost 30:1. That is to say, a thirty-fold change in attachment strength was observed for an array of fibers when it was loaded to a low preload before being retracted at thirty microns per second versus when loaded to a high preload and retracted at the same velocity. Whereas the preload deforms the fibers and changes the contact area, the retraction velocity reveals viscoelastic effects' relation to adhesion. At fast retraction speeds the side contact provides more attachment which decreases the adhesion control ratio, and at slow retraction velocities the fibers have time to regain their original shape, reducing the effective contact area at the time of pull-off.

If this information is to be useful in designing a one degree of freedom gripper, it should be noted that the adhesion controllability ratio does not take into account the actual preload values before which the maximum or minimum adhesion is observed. This may be in an important consideration because when the preload which results in the maximum measured adhesion is near the region of preload which results in instability, the values will be sensitive to small variations in preload. A different metric that reduces the control ratio



Figure 2.12: (a) Adhesion versus preload data shows an initial peak where tip contact is maximized and a drop off where the fibers bend sufficiently to remove the tips from contact with the substrate. The plateau after the drop off is where the sides of the fibers are in contact. (b) Taking the fraction of the maximum measured adhesion force over the minimum measured adhesion force for the same retraction velocity gives the adhesion control ratio. The highest control ratio observed, 30:1, was at retraction speeds of 30  $\mu m \, \text{s}^{-1}$ .

but ensures insensitivity to variations in preload may be more appropriate if applying this data to production level tasks where yield and repeatability are more important. Even so, the current adhesion characterization is sufficient to robustly pick and place certain parts to and from a substrate, as seen in Figures 2.13 and 2.14.

#### **2.3.6** Demonstration of manipulation

Using the proposed vertical or shear displacement based contact area control of the micropillars, we could demonstrate pick-and-place manipulation of microparts. Such adhesion control can be seen in an assembly task in Figure 2.13, where the indentation of the pillar into the silicon microplatelet is critical for pick-and-place manipulation. With a loading condition of 4  $\mu$ m of compressive displacement, the flat tip pillar tip made good contact with the part and could lift it off of the glass slide as demonstrated in Figure 2.13c. After moving to the desired location above the first part, the second part was released by increasing the downward displacement until the flat tip pillar lost tip contact (Figure 2.13e). When the pillar was retracted after tip contact was lost, the adhesion was low enough to release the second part on top of first (Figure 2.13f) thus beginning the assembly of a microstructure.

The same principle used to control a single angled micropillar's adhesive state can be applied to arrays of angled micropillars. A  $4x1 \text{ cm}^2$  glass cover slip was picked up and placed down with a 10x10 array of round tip micropillars (see Figure 2.14) demonstrating the extensibility of this approach to larger length scales and heavier parts. Figure 2.14 demonstrates the macroscale manipulation capability of a 10x10 round tip pillar array. In frame (a), the adhesive is brought into contact such that it can pick up the glass coverslip (weight of ~3.9 mN) as seen in frame (b). By compressing the pillars until bent, (c), the adhesive forces is reduced sufficiently to release the coverslip back to the glass substrate, (d). The insets are representative structure geometries.



Figure 2.13: Video snapshots from an inverted microscope show the steps of pick-and-place manipulation of the silicon microplatelets: (a) The micromanipulator contacts the first part, (b) picks it up from the substrate, and (c) brings the first part in contact with the second. (d) Compressive vertical displacement bends the pillar. (e) The pillar is slowly retracted. (f) The microassembly is completed.



Figure 2.14: Figure of video stills from a demonstration of the macroscale manipulation capability of a 10x10 array of round tip micropillars. The cover slip has been outlined and schematics representing the deformed state of any given pillar have been included to guide the reader. (a) The array is vertically displaced to sufficiently compress it to form a large contact before (b) retracting rapidly and picking up the glass cover slip. (c) When brought into contact again, vertical displacement control is utilized to compress the array of round tip pillars and induce edge contact, (d) such that retracting the array slowly will enable the cover slip to be released.

## 2.4 Discussion

## 2.4.1 Picking, holding and releasing models of manipulation

The universal van der Waals forces which act between surfaces are the roots of adhesion of the micropillar to the part and to the substrate, while the pull-off force depends on contact geometry, which we control through vertical or shear displacement. There are three conditions which are of interest to the design and implementation of a gecko-inspired pillar micromanipulator: picking, holding and releasing conditions. From experimental results, the behavior of the microstructure under loading was observed (Figure 2.6), which directs us to develop an analytical expression for the critical stages of a pick-and-place manipulation process (Figure 2.15). The geometry and deformation of the pillar in response to different loading conditions controls the contact area between it and a part and consequently its pull-off force.

## Picking

The pillar is able to pick the part up from a substrate as long as the picking force is greater than the sum of the part to substrate adhesion,  $F_{S1}$ , and weight of the part,  $F_W$ :

Picking Condition: 
$$F_P > F_{S1} + F_W$$
 (2.1)

For the rounded tip, the contact is approximated to occur between a sphere and a plane [65],

$$P_{sphere} = \frac{3}{2}\pi w_f R , \qquad (2.2)$$

and for the flat tip, the contact is approximated as a flat punch [172]

$$P_{flat} = \sqrt{6\pi a^3 K w_f} \ . \tag{2.3}$$



Figure 2.15: The micromanipulation process flow: (a) approaching, (b) contacting the part gently, (c) picking up the part, (d) holding while the part is transferred, (e) approaching a new location or substrate and (f) bring the part into contact. To release the part we can utilize vertical displacement control (VDC) or shear displacement control (SDC). For VDC, the process begins with (g) compressing until the pillar is bent and the contact area is significantly decreased, then (h) retracting, and finally (i) releasing the part. Utilizing SDC is identical except for the use of shear displacement, (g)\*, instead of additional vertical displacement to peel the tip of the pillar. The three critical cases for manipulation are, (c) the picking case, (d) the holding case and (h) the releasing case. The zoomed in call-outs of these three critical cases depict the forces experienced by the part and the size of the spherical contact representing the pillar-to-part interaction.

In both equations, the work of adhesion of the interface is  $w_f$ , and the effective Young modulus, K, of the system is

$$K = \frac{4}{3} \left( \frac{1 - \nu_1^2}{E_1} + \frac{1 - \nu_2^2}{E_2} \right)^{-1},$$
(2.4)

where  $\nu_1$  and  $\nu_2$  are the Poisson's ratios of the interface materials, and  $E_1$  and  $E_2$  are the Young moduli of the interface materials. In the flat punch equation, a is the radius of the flat tip, and in the sphere contact equation, R is the radius of curvature of the round tip.

The picking condition also depends on viscoelastic effects, which could increase the pull-off force exerted by the pillar when retracted from a surface with a high speed (i.e. high strain rate). Viscoelastic effects can be considered to be composed of macroscale, internal, material effects, called *bulk* viscoelasticity, and microscale, interfacial, chemical-bond effects, called *surface* viscoelasticity. Bulk viscoelasticity acts to effectively stiffen the structure under rapid loading or unloading. Surface viscoelasticity modulates the effective work of adhesion. Both bulk and surface viscoelasticity can contribute to increased pull-off forces in our experimental conditions. However, due to the micron scale deformations of our pillar, we can ignore bulk viscoelastic effects in approximating a model of the picking condition as suggested by theory [107] and as implemented empirically in previous work [118].

The surface viscoelasticity has been empirically shown to be related to the thermodynamic work of adhesion by a scaling factor,  $w_f^{visco}(v) = \kappa(v)w_f$  [173]. The scaling factor,  $\kappa$ , represents the relative importance between the glassy behavior of a viscoelastic material when rate of loading approaches infinity and the rubber like behavior when rate approaches zero. Empirical evidence points to a power-law dependence by the scaling factor,  $\kappa$ , on retraction velocities [174], which suggests that the scaling factor can be rewritten as  $\kappa(v) = av^b + c$ , where a, b, and c are empirically determined constants and v is the rate of loading. The effect of pull-off speed on pull-off force was observed to be positive for picking (Figure 2.11), which matches theory [173].

### Holding

The holding condition can be considered to be effectively static where its governing equation is of the maximum adhesive force between a purely elastic sphere and an atomically smooth, rigid plane for the case of the rounded tip and a purely elastic cylindrical punch contacting a rigid plane for the case of the flat tip. Assuming there are no external disturbance forces, the limiting case for the holding condition is when the weight of the part  $(F_W = m_{part}g)$  is greater than the adhesive force, and so holding is feasible only when the following inequality of forces is satisfied:

Holding Condition: 
$$F_H \ge F_W$$
 (2.5)

In the holding condition, we can use the non-viscoelasticity modified equations for sphere contact, Equation 2.2, and flat punch contact, Equation 2.3. High instantaneous forces allow the pillar manipulator to pick up a heavy part, but the part may fall while being transferred; so, lower pull-off speeds are a better empirical estimate of the actual holding force of the manipulator.

#### Releasing

The releasing condition resembles the picking condition in that the attraction of the part to the substrate plays a role as well as the rate at which the pillar is pulled away from the part. The objective of the releasing condition is to minimize the adhesive force between the pillar and the part,  $F_R$ , for a given combination of substrate to part adhesion,  $F_{S2}$ , and part weight  $F_W$ :

Releasing Condition: 
$$F_R < F_{S2} + F_W$$
 (2.6)

The releasing condition for both flat tip and round tip pillars is characterized by contact along the edge, which is relatively smaller than the picking or holding conditions. The edge contact is achieved either by vertical or shear displacement control of the pillar to induce deformation at the tip. Additionally, the pull-off speed during releasing is kept as low as possible to minimize any viscoelastic contributions to the adhesive force (see Figure 2.11). The silicon microplatelet has a weight that is four orders of magnitude less

than the smallest measured adhesive force, so the part must have an attractive force,  $F_{S2}$ , to the substrate it is being released to in order for the release to be successful.

In addition to the force inequalities, another consideration in characterizing the performance of the micromanipulator is the displacement of released parts in the direction of the pillar tilt. As the pillar with attached object is compressed into the substrate it slides and bends, which laterally displaces the part that it is carrying. An analysis of this lateral displacement showed that it was an order of tens of microns when the part was being released on top of a second part (Figure 2.13e) but on the order of microns or less when deposited on to a clean glass slide. The lateral displacement must be taken into account when conducting micromanipulation and assembly tasks precisely.

## 2.4.2 Modeling the contact-area of a round tip pillar

The importance of the simulation is in helping to explain the mechanisms at work in attachment and detachment, and also as a design tool for implementing the microstructure array as a gripper. As a design tool, it predicts the preload for which maximum contact area is achieved as well as the region where the contact area decreases precipitously. The attachment strength is proportional to the contact area, so the simulation is effective as a predictor of adhesion behavior.

The initial adhesive behavior of the fiber array for low preloads is analogous to the contact area behavior of a sphere-plane interface under load as predicted by the Johnson-Kendall-Roberts (JKR) model [65]. However, as the fiber array preload approaches the region of instability the behavior deviates more and more dramatically. It may seem obvious that the behavior of the array should deviate from such a simple model, because the interface is between a plane and a surface composed of microstructures, not between a hemisphere and plane. The question which arises is why should it match in any regime, and is addressed by the fact that each individual fiber in the array has a tip similar to a hemisphere contacting the glass slide (Figure 2.1). The eventual deviation at higher preloads occurs because these individual hemispheres are at the tip of a fiber which bends like a fixed-free beam under angled load. This bending proves to be important because it eventually rotates enough of the tip away from the contact substrate to decohere completely



(Figure 2.16).

Figure 2.16: These side view video stills of the fiber shows the shape as the fiber displaces due to the preload. White outlines and highlights have been added to help visually define the shape of the fiber and contact substrate.

To explain the behavior of the fibers, we hypothesize that the attachment strength is proportional to the contact area before pulling off the fiber array and that with increasing preloading the contact area of a single fiber is influenced by two competing factors: the increasing contact area as predicted by JKR, and the decreasing contact area from rotating the fiber tip as predicted by beam bending. To test this hypothesis, a model was created that solves for the effects of these competing factors on the contact area. An analytical solution exists for the contact area relation to load [65], but the large-deflection analysis of the beam is solved computationally [175]. Parameters related to the fiber geometry were taken from SEM, optical micrographs, and surface profiler data. Physical parameters, such as Young moduli, work of adhesion, etc., were taken from Aksak et al.[118] (see Table 2.1).

The fiber tip was seen from SEM micrographs and profilometry to have a concave curvature, which was approximated to be spherical and characterized to be of radius,  $\rho = 43.3$  nm (Figure 2.1). One can imagine that the surface of the tip is inscribed within a concentric and coradial sphere, as seen in figure 2.17. The contact area between a sphere

Fiber Type	Round	Flat
Length	75 μm	95 µm
Height	72 µm	89 µm
Angle of inclination	16°	20°
Diameter	Elliptical (35 µm,45 µm)	35 µm
Radius of curvature of tip	380 µm	N/A
Young modulus	9.8 MPa	9.8 MPa
Work of adhesion	$32 \text{ mJ} \text{m}^{-2}$	$32 \text{ mJ} \text{ m}^{-2}$

Table 2.1: Fiber Parameters

and a plane has been investigated in detail by many researchers, and several models exist, but the best for our case is the one described by Johnson, Kendall and Roberts, called the JKR model of adhesive contact [65]. According to the JKR model, the radius of the circular contact area of a sphere and a plane,  $R_{JKR}$ , depends on the material properties, surface energies and external loading:

$$R_{JKR} = \left[ \left(\frac{\rho}{K}\right) \left( P_n + 3\pi\rho W_f + \sqrt{6\pi\rho W_f P_n + \left(3\pi\rho W_f\right)^2} \right) \right]^{1/3}$$
(2.7)

where  $P_n$  is the compressive external loading force,  $W_f$  is the work of adhesion of the surfaces, and K is the effective modulus of elasticity as defined above (Equation 2.4).

However, as the fiber is compressed by the external load, it bends and the tip rotates, as seen in video stills from experiment (fig 2.16). As the fiber deforms, the tip can be imagined to slip along the inside of the sphere which is defined by the curvature of the tip. The angle of rotation of the tip,  $\theta$ , can be found by using an analysis of large deflections of beams. No explicit analytical form of the solution relating tip end angle and load exists, so the relationship is found computationally.

Viewed directly head on along the central axis, the cross section of the tip appears as a circle, but as it rotates, it takes on an elliptical cross section. The actual contact area formed by the fiber is not of the JKR predicted spherical indentation, but of the intersection between the spherical indentation circular cross section, which remains at the top of the sphere, and the cross section of the tip, which slides down the side of the sphere (Figure 2.17). Viewed from the side, the center of the tip's cross section can be said to have migrated a distance,



Figure 2.17: As the load increases from (a) to (d), the actual contact area, highlighted in white, first increases, (b), then decreases, (c), and finally disappears, (d).

 $\delta_x$ , away from the center of the JKR predicted cross section (Figure 2.18). The tip's cross section changes its shape from circular to elliptical as the tip end angle,  $\theta$  increases, but approximating this change in shape as a change in radius of a circle simplifies the math. The radius of the approximated tip cross section is then defined to be,  $R_{tip} = R \cos \theta$ , where R is the undeformed tip radius.





Figure 2.18: A side view schematic of the geometrical considerations in the model of the contact process of the round tip pillar. The curvature of the round tip,  $\rho$ , defines the size of an imaginary sphere with which the tip is circumscribed. The contact patch of this imaginary sphere as predicted by the JKR theory is  $R_{JKR}$ . The actual area of the tilted pillar tip (tilt angle is  $\theta$ ) as projected to the contact plane is  $R_{tip}$ . The lateral displacement of the tip due to loading is  $\delta_x$ .

Viewed from above, one can see that the actual contact area is an asymmetric lenslike shape at the intersection of two circles, one for the JKR contact area, one for the tip geometric area. The common chord at the intersection of the circles divides the areas into two sectors, the JKR sector,  $S_{JKR}$ , and the tip sector,  $S_{tip}$ . The area sectors are defined as

$$S_{JKR} = \frac{1}{2} R_{JKR}^2 (2\epsilon - \sin 2\epsilon) \tag{2.8}$$

$$S_{tip} = \frac{1}{2} R_{tip}^2 (2\gamma - \sin 2\gamma)$$
 (2.9)

The angle,  $\gamma$ , is geometrically defined as shown in figure 2.19, and can be found by using the law of cosines:

$$\gamma = \arccos\left[\frac{R_{JKR}^2 - (R_{tip}^2 + \delta_x^2)}{-2R_{tip}\delta_x}\right]$$
(2.10)

The angle,  $\epsilon$ , is also shown in figure 2.19 and is defined through direct trigonometric relations:

$$\epsilon = \arctan\left[\frac{R_{tip}\sin\gamma}{R_{tip}\cos\gamma - \delta_x}\right]$$
(2.11)

Finally, the actual contact area can be written as the combined area of the JKR cross section and tip sector minus the JKR sector:

$$A_{contact} = \left(\pi R_{JKR}^2 + \frac{1}{2}R_{tip}^2(2\gamma - \sin 2\gamma)\right) - \frac{1}{2}R_{JKR}^2(2\epsilon - \sin 2\epsilon)$$
(2.12)

In figure 2.20 the simulated contact area is compared with the empirical adhesion results at a single retraction velocity,  $30 \ \mu m \ s^{-1}$ . The simulation results are normalized to the maximum contact area and the graph axes are adjusted to fit the simulation curve height to the empirical adhesion height. The model captures the behavior of the fibers closely, predicting the preload that gives maximum adhesion within 1%, and the center of the region of instability within 40%.

The simulation confirms our original hypothesis that competing mechanisms influencing contact area during preloading is an accurate predictor of attachment strength during pull-off. The understanding of the mechanism of fiber decohesion is critical for controlling



**Top View** 

Figure 2.19: A top view schematic of the geometrical considerations in the model of the contact process of the round tip pillar. The contact patch of this imaginary sphere as predicted by the JKR theory is  $R_{JKR}$ . The actual area of the pillar tip as projected to the contact plane is  $R_{tip}$ . The lateral displacement of the tip due to loading is  $\delta_x$ .



Figure 2.20: A representative adhesion versus preload curve (30  $\mu$ m s<sup>-1</sup> retraction velocity) is compared to the simulated contact area which is normalized to the maximum contact area

fiber array attachment/detachment and improving yield and repeatability in future gripping and pick-and-place applications.

When comparing the simulated contact area with the empirical adhesion measurements, the retraction velocity is important to consider because at low velocities the fibers have the opportunity to bend back into place and re-establish tip contact with the substrate. The higher the retraction velocity, the more closely the empirical adhesion curves will match the simulated contact area curves, because instantaneous tensile loading will be directly proportional to the contact area whereas finite retraction velocities allow for bulk viscoelasticity to effect the contact area during retraction.

Another important factor to take into account is the side wall attachment of the fibers to the contact substrate when they are completely bent. For higher retraction velocities, this side wall attachment gives increasing attachment strength for increasing preloads. As a possible future work, fabricating fibers with non-adhesive sides would reduce this effect and possibly improve the ratio of high to low attachment strength observed. This may be achieved by protecting the tip surfaces and chemically altering the sides with a reactive gas, or by creating molds with roughened side walls.

# 2.4.3 Simulation of stress distribution across the surface of the flat tip pillar

The sharp switching from the pick to release states of the flat tip pillar originates from the stress distribution on its tip surface. From contact area micrographs, it was observed that the tip spontaneously peels away starting from the "toe", the edge furthest from the base of the pillar, once a critical compressive displacement is applied (Figure 2.6c). A finite element model, in COMSOL Multiphysics 4.0a, of the pillar system was created with a prescribed displacement boundary condition at the pillar base and a roller boundary condition at the pillar tip. The model boundary conditions were consistent with empirically observed boundary conditions: video reveals that the pillar tip slides along the contact substrate before peeling. Visualizing the interface pressure along the center line of the tip contact reveals that the uneven stress distribution actually achieves significant tensile stress for a region of the tip near the toe edge (Figure 2.21). This result is consistent with



observation, but runs counter to first order analytical approximation by Aksak et al. [118].

Figure 2.21: Finite element modeling of the angled flat tip micropillar reveals that the "toe" section of the tip surface is under tensile stress when the vertical displacement applied at the backing is compressive. The plotted lines are labeled with vertical displacement values and shaded from light to dark to represent low to high degrees of compression. The insert shows a schematic of the pillar under loading conditions with dashed grey lines indicating how cross sectional position is mapped on the tip.

#### Modeling and Simulation Results

The experimental and simulation results mirror the findings of other researchers that controlling contact area using mechanical effects is effective in controlling adhesion. Applications have been demonstrated in an industrial-scale manipulation task [5], wall-climbing robots [22, 158], and micro-manipulation and fabrication of silicon parts [24, 108]. The method of controlling adhesion presented in this work can be easily adapted to a one degree of freedom manipulator. One added complexity is the requirement of feedback control, but the sensor information can be fairly coarse, due to the narrow band of instability seen in figure 2.12 which should be avoided to ensure repeatability. Although force feedback may be the obvious choice to implement control, it has been shown that visual tracking of fiber bending is also an effective source of sensor feedback [176].

## 2.5 Conclusions

In this chapter, we have presented an application of synthetic gecko-inspired angled elastomer micropillars to the task of manipulating and assembling parts ranging in size from micrometer to centimeter scale. These manipulators can work with only one degree of freedom actuation for part pick and release due to the pillar mechanical instability during vertical compression, but two degrees of freedom motion control has also been demonstrated and improves the pick-and-place performance. In addition to manipulating various parts and structures of different sizes, the manipulators can be used to assemble silicon microplatelets of planar geometry in a 2.5D assembly scheme.

Future work will seek to improve the consistency, repeatability and fine control of the manipulation scheme. Specifically, we intend to utilize rotational stages to help orient parts and visual tracking to automate the pick and place process. Fabricating smaller pillars has been a challenge in the community, but doing so would allow for the manipulation of even smaller parts, or large parts with greater control. We anticipate that all these improvements will not only expand our ability to safely manipulate fragile microparts, but also will lend insight into the critical contact self-cleaning ability of geckos' micro/nanohair covered feet.

# Chapter 3

## Contact Self-Cleaning of Gecko-Inspired Adhesives

## 3.1 Introduction

Geckos have an uncanny ability to attach to and run along smooth walls and ceilings with nothing more than the pads of their toes. After millennia of interest [34] and over a century of scientific investigation [2, 177], in the last decade engineers and scientists have successfully uncovered the principles of the gecko's impressive adhesive capabilities [12, 37]. Furthermore, gecko-inspired adhesives synthesized in the lab have been demonstrated to compare favorably to the gecko's in attachment strength. However, no synthetic gecko-adhesive has matched its natural counterpart in one key regard: the ability to resist contamination, or regain adhesion after contamination, through normal use. Furthermore, we lack an understanding of what the mechanics of self-cleaning are, and which important design parameters enable self-cleaning in structured adhesives.

After extensive physiological characterization of the micro and nano structures covering the bottoms of gecko feet, and macro and micro scale experimentation of the gecko's attachment capability, certain principles have become codified by the community [6, 28]. The seven functional properties that are characteristic of the gecko adhesive system are: (1) van der Waals adhesion, (2) high pull-off to preload forces ratio, (3) low detachment force, (4) anisotropic attachment, (5) anti-self-matting, (6) non-sticky default state, and (7)

#### 3. Self-Cleaning

self-cleaning. Of these properties, the first six have been achieved in synthetics [5, 9, 125]. The seventh property is the final and most challenging principle to be implemented in synthetics. The difficulty in creating self-cleaning adhesives is in some part due to a lack of understanding of the gecko adhesive. It seems that though all gecko setae are similarly stiff, we still do not know how variations in structural morphology might affect the ability of different types of gecko to self-clean [178]. In fact, in might be that the gecko setae represents an optimal design, not only for adhesiveness, but also for its ability to remain clean [33]. If we, as a research community, can surmount the challenge of creating self-cleaning, geckoinspired adhesives, then we can present it as a mature technology for use in the real world. Of the hundreds of papers on gecko adhesion and its synthetic facsimiles only a handful exist that propose mechanisms and present evidence for self-cleaning or contaminationresistance [10, 11, 14, 130, 179, 180]. Hansen and Autumn first demonstrated that geckos can recover toe attachment strength even after complete clogging of the gecko's arrays of long thin fibers (setae) by 5 µm diameter silica-alumina ceramic spheres [11]. It was shown that the attachment strength of an isolated array of setae dropped to 40% of the clean adhesion strength after contamination, but rebounded to 70% of the clean adhesion strength after 8 simulated steps. The self-cleaning of the gecko foot seems to occur through normal use, as the gecko shears its foot along a surface it regains lost adhesion. To mimic the natural motion of the gecko, a simulated stepping cycle was used, which consisted of a series of motions that pressed the setae against a clean glass substrate, then dragged the setae along the glass before being pulled away and repositioned over a clean patch. As a point of reference, a clean gecko toe attaches to a substrate with a maximum shear stress of over 200 kPa. However, a 40 g gecko only needs 20 kPa of attachment strength (10% of the clean adhesion) to hold up its weight with a single toe with a contact patch 5 mm in diameter, which is about the size of the tip of pencil eraser. Hansen and Autumn's seminal study used only one size of contaminating particle and did not show the mechanics of the cleaning process as the setae where sheared. This leaves a gap in our understanding of what the important parameters and what the precise mechanisms are for self-cleaning. Other mechanisms of cleaning natural and synthetic gecko adhesives have also been reported, included cleaning with compressed air [11], by contacting a conventional adhesive surface [10], through vibration [180], and by rolling droplets of water along the surface

of the adhesive [78, 152, 181]. Active cleaning methods have been proposed that utilize vibration, wax casting, and contacting to conventional adhesive tape [10, 180].

Wet self-cleaning exploits the lotus-leaf effect to enable water droplets to pick up and roll away dirt particles contaminating a hydrophobic surface. Although there is little evidence that such a self-cleaning principle is exploited by the gecko, this may be an easily applied feature for synthetic gecko-adhesives. As such, wet self-cleaning has been demonstrated for synthetic gecko-adhesives composed of arrays of carbon nanotubes (CNT) [152, 181] and for arrays of polyurethane microposts with mushroom shaped tips [78]. Kim et al. showed that rolling droplets of water cleaned the surface of mushroom tipped posts (in a process called the lotus effect). Kim et al.'s posts have significant adhesion and friction, but dry contact self-cleaning was not reported [78]. We feel that dry, contact-based self-cleaning is a more practical principle to apply to synthetic geckoadhesives, and we focus entirely on it for our investigation in this work.

Lee and Fearing [130] demonstrated dry, contact-based, self-cleaning of high aspect ratio fibers which have significant friction but limited normal pull-off adhesion. They showed that arrays of fibers 18  $\mu$ m in height and 300 nm in diameter would lose all adhesive capability when contaminated with 6  $\mu$ m diameter gold spheres, but would then recover 33% of the clean attachment force after 30 shearing cycles similar to the simulated steps used by Hansen and Autumn [11]. Lee and Fearing used different size particles for contamination tests, and showed that there is a sharp delineation between "cleanable" and "uncleanable" particles. They show that their nanofiber array can recover adhesion after contamination by particles 3 or 4  $\mu$ m in diameter, but cannot recover any adhesion when contaminated with particles 6 or 10  $\mu$ m in diameter. The clean array of nanofibers showed initial shear attachment strengths of 8 kPa, less than 4% of the clean shear adhesion of the natural gecko toe. Although the first work to show contact self-cleaning of synthetic gecko-inspired adhesives, Lee and Fearing used a narrow range of particle sizes, only one size of nanofibers, and did not demonstrate the microscale processes that lead to self-cleaning.

Gorb et al. [14] presented evidence for contamination resistance of arrays of micropillars with mushroom-shaped tips. They showed that the mushroom tips conformed to small dirt particles in such a way that the tips of the pillars still make sufficient contact with a substrate to retain a large portion of the clean adhesion. Carbone et al. [80] presented a model

#### 3. Self-Cleaning

that suggests that as long as the dirt particle diameter is much smaller than the mushroom tip diameter, then the particle will not cause a defect to propagate at the contact interface. This suggests that the mushroom tip will detach as it normally would without the presence of the particle, which can be considered a form of contamination resistance. However, these works did not investigate the possibility of recovering adhesive performance through self-cleaning.

The field of structured adhesives, both natural and synthetic, has come to something of an inflection point, with a drop in scholarly output on the topic in the last few years [21]. Recent reviews of the field point to the self-cleaning property as a significant feature still missing in synthetic gecko-inspired adhesives [28, 29]. We propose that in addition to the significant technical challenges in fabricating robust, long lasting structured adhesives, we also need to develop scientific knowledge on the principles of self-cleaning that will make these same adhesives practical in the real world. As a case in point, Kwak et al. [10] presented a gecko-inspired adhesive as a replacement of traditional acrylic adhesives used on medical diagnostic electrodes, but in a review of the field, Karp and Langer [113] point out that such an adhesive must, among other problems, contend with contamination by shedded skin cells.

To that end, the objective of this work is two-fold: to reveal possible avenues to solving the challenge of creating self-cleaning synthetic gecko adhesives and to present a possible solution to the challenge. What is lacking in previous studies of self-cleaning is a systematic analysis of how the sizes of dirt particle and adhesive microstructure are related, and what the precise mechanisms of self-cleaning are. By investigating particles ranging in size from 1 to 250  $\mu$ m in diameter, and three sizes of mushroom-tipped micropillars (tip diameters of 20, 30 and 95  $\mu$ m), we find that there are two modes of self-cleaning that can result in adhesion recovery: depositing of particles to a clean substrate, and embedding the particles into the array of adhesive structures. This is in contrast with previous results which only consider particles much greater in diameter than the fibers and only propose self-cleaning by depositing [11, 130] or rolling [179]. The development of self-cleaning in gecko-inspired adhesives is the critical next step required for the field to produce technological solutions such as: extremely strong, reusable medical bandages; power-efficient, robust climbing robots; and industrial robotic manipulators for tiny parts and large fragile devices.



(a)

(b)





Figure 3.1: (a) SEM image of an array of small micropillars with large contaminating particles, and (b) the same array after dry self-cleaning against a glass substrate, showing that the contaminating particles embed to the backing layer. (c) Medium pillars contaminated with particles of similar size, and (d) after partial cleaning. (e) Large micropillars contaminated with much smaller particles have most of the contamination on the tips, but (f) after self-cleaning, most of the particles are embedded in between the array.

## **3.2** Materials and Methods

The arrays of polyurethane microfibers with mushroom tips were fabricated through previously demonstrated lithographic and dipping processes combined with soft mold casting [118]. The polyurethane used (ST-1060, BJB Enterprises) had a stiffness of 2.9 MPa and has a work of adhesion to glass of 93 mJ m<sup>-2</sup> [77]. The adhesives were manually cut into square patches 500x500  $\mu$ m<sup>2</sup> in area and mounted onto a clear acrylic peg which acted as the handling substrate.



Figure 3.2: Micrographs of the three sizes of micropillars used in this study, with dimensions in microns. (a) The small micropillars are 25  $\mu$ m in height and 20  $\mu$ m in diameter at the tip, (b) the medium pillars are 50  $\mu$ m in height and 30  $\mu$ m in diameter at the tip, and (c) the large micropillars are 105  $\mu$ m in height and 95  $\mu$ m in diameter at the tip. The scale bar in the lower right is the applicable to all three micrographs.

The testing protocol was carried out on a custom 3-axis motion control system built onto an inverted view microscope (Eclipse LE200, Nikon) and was controlled through custom software. The linear stages (MFA-CC and VP-25XA, Newport) were used to move the adhesive sample in the Z-axis to bring it in contact with a glass slide (Microscope Slide, Pearl) which was moved in the Y-axis to apply shear to the adhesive sample. The normal forces applied to the adhesive sample were captured with a load cell and signal amplifier (GSO-50 and TMO-2, Transducer Techniques) and transmitted to our test computer via a data acquisition board (NI PCI-6259, National Instruments). Since the contact was between two flat surfaces, alignment was achieved through two rotational stages (GON40-U, Newport). The visual information was captured via a color digital video camera (DFW-X710, Sony) connected to our test computer. The contact and cleaning processes were captured

#### 3. Self-Cleaning

via custom software that recorded and time-stamped the force data and video feed for later analysis.



Figure 3.3: (a) Computer model rendering of the adhesion testing system built on an inverted view microscope. (b) Close up of the model rendering and the (c) photograph of the actual testing system show labeled components: A - goniometer, B - manual x and y axes stages, C - motorized y axis stage, D - load cell, E - light source, F - adhesive sample, G - glass contact substrate, H - microscope objective.

As our idealized contaminant, glass spheres of dimensions ranging in sizes from 1 to 250  $\mu$ m were used (soda lime glass microspheres, Cospheric). To create a disperse monolayer as our simulated dirty surface, we took one of three approaches depending on the size of the microspheres. For microspheres over 150  $\mu$ m in diameter, it was sufficient to manually pour them on to a glass slide, where they settled through gravity into a monolayer.

#### 3. Self-Cleaning

Microspheres with diameters between 15 and 150 µm were poured onto a glass slide then pressed with a glass cover slip to create a monolayer. For microspheres smaller than 15 µm in diameter, we first dusted an aluminum surface with the spheres, then built up an electrostatic charge on a glass slide by rubbing it with a piece of lens paper, then brought the glass slide near the dusted surface until the spheres were attracted to the glass slide. The contamination of the array of microfibers was performed by pressing the array into the monolayer of microspheres at 25  $\mu$ m s<sup>-1</sup> until a preload of 50 mN (200 kPa) was achieved, then the array was retracted at the same speed. The small micropillars were preloaded with 10 mN (40 kPa) Adhesion measurements were conducted by a simple compressive loading then unloading motion perpendicular to the contacted substrate. The compressive load achieved before pulling the adhesive sample away, called the preload, was 50 mN (200 kPa) for all adhesive samples except the array of small pillars, which we loaded to 10 mN (40 kPa). The preload was chosen to maximize the attachment force and was determined by analyzing the adhesion for preloads ranging from 1 mN (4 kPa) to 145 mN (580 kPa). The cleaning cycle was conducted as follows: to begin the pillar array was pressed to a glass slide at a rate of 25  $\mu$ m s<sup>-1</sup> until a preload of 100 mN (400 kPa) was achieved, then the glass slide was displaced laterally for 750  $\mu$ m at 50  $\mu$ m s<sup>-1</sup>, and finally the fiber array was retracted at 25  $\mu$ m s<sup>-1</sup>. After each cleaning cycle, an adhesion measurement was taken as a means of tracking how much adhesion was recovered at each step. The direction of lateral displacement was alternated for each cleaning cycle to prevent any plastic deformation of the backing layer. The glass slide was cleaned as needed by wiping with a dry piece of lens paper then with compressed air.

## 3.3 **Results and Discussion**

Through experimentation we observed two modes of self-cleaning: deposition, where particles were transferred to the clean contact substrate, and absorption, where particles were embedded into the array of micropillars itself. Figure 3.6 represents these two modes of self-cleaning and which we label as depositing and for embedding. What is important about these observations is that the act of recovering the initial clean adhesion strength is not necessarily related to actually removing dirt from the adhesive. The principle of self-cleaning



Figure 3.4: (a) Contamination is carried out by moving the array of micropillars into contact with a monolayer of microspheres dispersed on a glass slide. (b) The cleaning process is conducted by pressing the array into a clean patch of a glass slide, then displacing the glass substrate laterally before retracting the array. (c) Adhesion measurements are taken after each cleaning cycle against a clean patch of a glass slide.
## 3. Self-Cleaning



Figure 3.5: (a) Microscopy images of the array of large micropillars contaminated with small spheres (Regime 3) during a cleaning cycle shows how the pillars collapse and the backing layer deforms due to the applied shear displacement. The final image is a background-subtracted micrograph of the contact substrate showing the residue of deposited microspheres. (b) Images of the same size of micropillars contaminated with much larger particles (Regime 1) shows that the sphere makes contact with the glass substrate and is rolled off of the tips of the micropillars, leaving a clean array in the final inset image. The arrows indicate the direction of motion of the contact substrate.

is in recovering adhesion, and this is possible by just removing contamination from the tips of the adhesive structures. Where the contaminant particles end up is not a critical part of self-cleaning.



Figure 3.6: Schematic of the two modes of self-cleaning observed: (a) embedding particles into the array of adhesive structures, and (b) deposition of the particles to a clean substrate.

We investigated the importance of the ratio of micropillar radius to particle radius by dividing the relationships into three regimes. In regime 1 (R1) the contaminant particles were much greater in size than the radius of the tip (at least 2 times the tip radius), in regime 2 (R2) the particles were anywhere from half to twice the tip radius, and in regime 3 (R3), the particles were less than half the tip radius (Figure 3.7a). When particles diameters where much larger than the micropillar tip diameters (regime 1), self-cleaning performance



Figure 3.7: Self-cleaning is dependent on the relative sizes of contaminating particles and the characteristic length of the micropillars. The characteristic length can be (a) the tip radius, (b) the length of the fiber, or (c) the spacing between fibers. In the case of tip-radius dependency, we defined three regimes for when: (R1) the particle radius is greater than twice the tip radius, (R2) about the same size, and (R2) less than half the tip radius.

was maximized, closely followed by regime 2, and finally by regime 3 (Figure 3.8). Regime 1 self-cleaning saturated to 62.9% (S.D. = 34.7%, N = 220) of clean adhesion performance within 5 cleaning cycles, regime 2 self-cleaning saturated to about 56.2% (S.D. = 34.1%, N = 83) in 12 cleaning cycles, and regime 3 self-cleaning saturated to 34.1% (S.D. = 9.8%, N = 176) by 15 cleaning cycles. These results compare favorably with both the gecko and synthetic adhesive self-cleaning performance. Isolated arrays of gecko setae dropped to 40% of initial clean adhesion immediately after contamination, and after 4 cleaning cycles had recovered adhesion back up to 70% of the clean adhesion [11]. Synthetic geckoadhesives have been demonstrated to adhere with 33% of their clean adhesion strength after 20 to 25 steps [130]. We hypothesize that since the long thin fibers presented by Lee and Fearing make adhesive contact primarily in the manner of a line contact along the length of the fibers, that they will be dominated by a different set of critical parameters than geckos and tip-contact based synthetic adhesives. However, in the case of geckos and the synthetic adhesives presented in this work, the critical parameters for self-cleaning are the tip radius, the pillar height, and the spacing between pillars. It is important to note that these same parameters, in addition to material properties, have been presented in other works in schemes meant to optimize adhesive performance [105, 182].

We also investigated the ability of the arrays of micropillars to remain adhesive immediately after contamination, a property we call contamination-resistance. The first adhesion measurement after contamination, and before cleaning cycles began, revealed that regime 1 exhibits almost no contamination resistance. In regimes 2 and 3, adhesion remained at 20% and 17% respectively immediately post-contamination. There are two reasons for contamination-resistance for regimes where the particles are close to or smaller than the size of the micropillars. First, although the particles form a monolayer, they are stochastically distributed and some micropillars avoid contamination all together and hence retain clean tip surfaces. Second, when particles are much smaller than the micropillar, the mushroom tip can conform around the particle during subsequent adhesion measurements, a finding confirmed in previous works [14, 80].

In addition to self-cleaning, it is important for the adhesive to attach strongly in both its clean and cleaned states. As an example we analyzed the difference in adhesive performance of the large and small micropillars in regimes 1 (Figure 3.10). The large micropillars



Figure 3.8: This graph of cleaning coefficient versus cleaning cycles shows that different regimes of particle and micropillar sizes results in different rates of adhesion recovery and different saturation points.



Figure 3.9: This graph represents the contamination resistance within the different size regimes as determined by particle diameter and micropillar height. In regimes 1 and 2 and in the case of the flat, unstructured surface, the particle diameter is large enough to physically block the micropillars' tips from contacting the glass slide. In regime 3, the mushroom shaped tip of the micropillar conforms around the dirt particle to make contact with the glass slide, thus exhibiting some adhesion despite being contaminated.

had higher clean adhesion, demonstrating up to 35 mN of attachment force (140 kPa attachment pressure for the 500x500  $\mu$ m<sup>2</sup> patch). This is comparable to the gecko's foot, but it is important to note that our observations are for a small patch, and as patch sizes increase the observed performance tends to decrease [96].



Figure 3.10: Measured adhesion force versus cleaning cycle of the large micropillars (95  $\mu$ m tip diameter) contaminated with large particles (150-250  $\mu$ m diameter), which is in regime 1. The micropillar arrays (N = 3) eventually recovered 100% of the initial clean adhesion (SD = 14%).

These results revealed that there are multiple regimes of self-cleaning behavior, and that regime 1 has the least contamination-resistance but has the fastest adhesion recovery rate and highest cleaning coefficient. This finding implies that in designing a self-cleaning synthetic gecko-adhesive that it is important to make your micropillars as small as possible. Our microscopic observations indicate that in regime 1, almost no particles are deposited directly to the contact substrate, and instead the particles are rolled along the array until they reach the edge of the adhesive patch (Figure 3.5). The observation of the mechanics

of removing contaminants combined with the implication that regime 1 is the best case scenario for self-cleaning leads to the conclusion that a large adhesive patch of very small micropillars would require a large lateral displacement along a contact substrate to remove the particles (Figure 3.11a). If instead the large adhesive patch is split up into a series of smaller patches, with intervening spaces to act as particle traps, then the required displacement amount shrinks to the lateral size of a given small patch (Figure 3.11b). This finding supports utilizing hierarchy for designing synthetic gecko-adhesives. The top level of hierarchy, with the smallest structures, acts in regime 1 and easily rolls away larger particles, and the bottom level of hierarchy shortens the required sheared distance for cleaning. Additionally, the bottom level of the hierarchy effectively brings a second characteristic length into play, the height of the large base-level structures acts in regime 3 and embeds the particles.



Figure 3.11: (a) An adhesive patch of micropillars will require a lateral dragging distance greater than or equal to the patch length. (b) If the adhesive patch is split into a hierarchical array of micropillars on top of macropillars, then the required dragging distance will be reduced to an amount greater than the length of an individual macropillars.



Figure 3.12: The cleaning process can recover adhesion of the array of pillars, but it can also cause degradation as evidenced in these video stills. The loading and shearing of the array eventually causes the destruction of the pillars in the lower left hand section of the patch.

In this work we have presented evidence for the dry, contact-based self-cleaning of synthetic gecko-inspired adhesives. We observed significant adhesive recovery, far greater than any previously reported synthetic in both absolute attachment strength and relative recovery of pre-contamination attachment strength. Interestingly, our observations show that synthetic gecko-adhesives can recover the lost clean adhesion at a similar rate to that of the gecko. Although previous studies have proposed models that focus on how contaminating particles are deposited from the adhesive structures to the contact substrate, we propose that a more common mode of self-cleaning for synthetic gecko-adhesives made of relatively soft elastomers is embedding the particle within the array.

Furthermore, we observed that the relative size of contaminants to the characteristic size of micropillars within the array of synthetic gecko-adhesive strongly determined how and to what degree the adhesive could self-clean. In this study the pillar tip diameter, length, and spacing dimensions were coupled, but we hypothesize that a complete study of these dimensions will reveal which dimension defines the critical regime for when the particle is at a similar scale. In fact, looking at Hansen and Autumn's results with the actual gecko adhesive foot, we suspect that they were actually operating near this critical regime where some contaminating particles were only a little bigger than the spatulae (see Figure 4 in [11]).

Several other works have proposed that hierarchy may be a critical factor in creating a synthetic gecko-inspired adhesive that could reliably adhere to rough surfaces, but according to our observations, we propose that hierarchy is also critical for self-cleaning adhesives. Taking inspiration from gecko's adhesive structures, many synthetics are now made with anisotropic structures which lead to the control of adhesion, which may also prove to improve self-cleaning performance. We have used glass microspheres in this study as our simulated dirt particle, but it to increase the practicality of self-cleaning synthetic gecko adhesives, future works include the characterization of real-world contaminants and how the regimes of self-cleaning proposed in this work apply to them.

# Chapter 4

## Conclusions

After over a decade of considerable research interest and discovery, gecko-inspired adhesives are transitioning from a novel engineering material with great potential to a new technology with demonstrated capabilities. Even so, much of our understanding of the behavior and principles of gecko-adhesion is only academic and limited to contacting the adhesives to smooth, rigid surfaces. For applications to emerge more readily and actual devices to enter the public sphere, we must first understand the significance of several until-now-neglected principles. Specifically, viscoelasticity, soft-material contact, rough surface contact, and self-cleaning, are all topics which are only now emerging as dominant paradigms in gecko-inspired adhesion.

The role of viscoelasticity in the attachment strength of unstructured conventional adhesives is well known [173], and has been exploited for transfer printing micro-objects [108], but its role in gecko-inspired adhesives is less clear. The review of soft contact theory by Shull [107] indicates that viscoelasticity might be considered in two ways: the surface viscoelasticity that depends on molecular interactions at the interface, and the bulk viscoelasticity that dissipates energy internally over time. Initial experimental studies of the effect of viscoelasticity on gecko-inspired adhesion by Castellanos et al. [110] and Vajpayee et al. [109] confirm that increased strain rates result in increased pull-off forces. What is unclear is how viscoelastic contact theory can be applied to the array of structures, which is critical if we are to optimally design the next generation of gecko-inspired adhesives.

As has been demonstrated by the recent studies on medical device applications for

structured adhesives, what is still unclear is the role of highly-compliant substrates on adhesion. Kwak et al. [10] demonstrated a gecko-inspired adhesive on skin, but did not suggest design rules that others should follow in order to improve performance. On the other hand, Mahdavi et al. [111] showed counterintuitive results for gecko-inspired adhesion on organ tissue. We have a decade of research that tells us how gecko adhesives should behave against rigid substrates, but almost nothing that indicate whether these principles are similar for soft substrates.

Of the seven principles of gecko-adhesion outlined by Autumn [6], the one that is the least well understood and nearly non-existent in the literature is the principle of self-cleaning: how contaminating particles on the adhesive structures are removed through normal use. Current models of self-cleaning [11, 179] and current experimental results [14, 130] fail to explain the precise mechanisms for contaminant removal and also fail to identify important parameters for designing self-cleaning adhesives. Gecko-inspired adhesives are more attractive than traditional glue-based adhesives because they can exhibit high attachment strength and still be removed, but for them to be reusable, the gecko-inspired adhesives must reject contaminants to retain their strong adhesive properties.

Finally, we would like to predict what is possible for gecko-inspired adhesives if all of the current short-comings are resolved. Looking at the applications already under development, it seems clear that medical adhesives have great potential, and climbing robots might achieve significant utility. In consumer products, gecko-adhesives might replace Velcro®and zippers in clothing, and might become a critical component in sports gear, e.g. soccer goal keeper and rock climber gloves. The reversible, controllable nature of the adhesion, as well as its incredible bonding strength, suggests more impressive possibilities for gecko-inspired adhesives: perhaps it might act as a fastener for temporary or emergency construction. We might yet see rolls of single-sided and double-sided gecko-tape sold in hardware stores, not as a replacement for duct tape, but as a replacement for nails, staples and screws.

## 4.1 Contributions of this Work

## 4.1.1 Adhesion Control of Angled Micropillars

## **Preload Control**

Arrays of angled micropillars with round tips have been shown to exhibit changes in strength of attachment with increasing magnitude of compressive load (preload) before pull-off. This behavior lends itself to manipulation or gripping tasks where only one degree of freedom is needed to change the attachment condition. This variation in adhesion was shown to be controllable through loading and the speed of pull-off and was used to pick and place a glass slide (0.40 g) from and to a glass slide. The arrays of micropillars exhibited a factor of 30 reduction in attachment strength through higher preloads. In contrast, varying only speed for a given preload changed adhesion by a factor of 5. Additionally, a predictive model to find the preloads necessary to achieve this maximum controllability was developed.

## **Vertical and Shear Displacement Control**

We showed that the attachment strength of single angled micropillars with either flat or round tips could be modulated purely through displacement based control. The advantage of displacement control over load control was that it was not overly sensitive to input parameters causing mechanical instability in the pillar. We found that the picking-to-releasing attachment force ratio of a round tip pillar under vertical displacement control was about 25 to 1. The flat tip pillar under shear displacement control exhibited a picking-to-releasing attachment force ratio of about 40 to 1.

## **4.1.2** Model of contact area of the fiber under compressive load

The model is based upon the static analyses of contact area of a sphere indenting a halfspace as predicted by the JKR theory [65] and the large deflection of a fixed-free cantilever beam loaded at its free end [175]. It was hypothesized that the contact area when the fibers were compressively loaded would correlate with the adhesive force measured when they were pulled into tensile loading; the empirical adhesion results did, in fact, compare favorably with the theoretical contact area results, and appeared to be directly proportional.

## 4.1.3 Demonstration of Micropillar Arrays and Single Structures as Novel Manipulators

## Developed new fabrication techniques to create arrays of structured adhesives

Glass cutting and microlaser milling were utilized to create millimeter sized glass substrates with a controlled number of angled fibers for use in adhesion experiments and pick and place demonstrations. Previous work on angled fiber fabrication has been modified and refined to produce better and more repeatable arrays of structures, and work on these fabrication techniques are ongoing.

## Micromanipulation

Single angled flat tip micropillars were demonstrated as micromanipulators. We showed that we could reliably pick-and-place a  $100 \ \mu m$  on-a-side square silicon platelet, and even that we could place one platelet on top of another. This demonstration highlights gecko-inspired adhesives as having a potential impact in industries requiring the handling of fragile devices of almost any material properties and in almost any environmental conditions, including under water and in vacuum.

## Macromanipulation

We used arrays of angled, round tip micropillars as macromanipulators. We showed that thanks to the relatively large holding forces, we could pick up and hold a centimeter-scale glass cover slip before releasing it to a glass receiving substrate. This demonstration shows that the micropillars are a scalable manipulator, and can be applied to a wide range of part sizes.

## 4.1.4 Contamination-Resistant and Self-Cleaning Adhesives

Gecko adhesion is characterized by seven properties [6, 28, 30]: attachment dominated by van der Waals forces, high ratio of adhesion to preload forces, low detachment forces, anisotropic attachment, non-sticky default state, non-self-sticking, and dry, contact-based, self-cleaning. If we, as a research community, can master these principles, then we can present synthetic gecko adhesives as a mature technology for use in the real world. The first six properties are well represented in the hundreds of papers on gecko adhesion and its synthetic facsimiles, but only a handful of reports exist that propose mechanisms or present evidence for self cleaning [11, 78, 130, 179, 180].

## Demonstrated Significant Adhesion Recovery Through Dry, Contact Self-Cleaning

We were the first to demonstrate that arrays of mushroom tipped micropillars made from relatively soft polyurethane could exhibit self-cleaning through dry contact processes. We found that certain geometries of micropillars could recover almost 90% of their initial, clean adhesion strength through repeated-shearing based cleaning. This is especially significant because the gecko itself has been shown to recover a similar amount of its initial clean adhesion.

## **Formulated Regimes of Self-Cleaning**

In addition to demonstrating significant adhesion recovery, we formulated regimes of self cleaning that are characterized by the proportional dimensions of the micropillars and the contaminating particles. This is contribution will help the gecko-adhesive community because it presents a road map of interesting research that must be investigated to understand self-cleaning as a universal principle for all gecko-inspired adhesives.

## 4.2 Future Directions: Unsolved Challenges and Possible Applications

## 4.2.1 Translate Micromanipulation Research Results into Industrial Applications

Future work will seek to improve the consistency, repeatability and fine control of the manipulation scheme. Specifically, we intend to utilize rotational stages to help orient parts and visual tracking to automate the pick and place process. Fabricating smaller pillars has been a challenge in the community, but doing so would allow for the manipulation of even smaller parts, or large parts with greater control. We anticipate that all these improvements will expand our ability to safely manipulate fragile microparts.

#### Characterize Viscoelastic Behavior in the Micromanipulator

For the micropillar to be useful as an industrial micromanipulator, it must be able to perform its tasks quickly and repeatably. High rates of strain causes the elastomeric polyurethane to exhibit viscoelastic properties which can limit its utility, but could also be used to enhance the ratio of pick-to-release attachment forces. One viscoelastic behavior that has been observed was how large deformations of the angled micropillar could require long relaxation times before it regained its original shape, as can be seen in Figure 4.1. Characterizing these viscoelastic properties will allow us to implement higher speed manipulation tasks in a controlled and repeatable manner.

## 4.2.2 Improved Characterization and Modeling of Contact Process of the Micromanipulators

We have characterized the contact process of the flat tip and round tip micropillars through interferometric metrology, and suggested an explanation for how the contact process evolves through finite element modeling. However, the models were approximations that assumed no friction and a pinned interface between the tip of the pillar and the contact substrate. Additionally, the high minimum speed  $(1 \ \mu m \ s^{-1})$  of the motorized stage used

for the contact process, and the low frame rate (15 fps) of the video capture camera, limited our ability to characterize the degree to which bulk viscoelasticity could effect the contact evolution during loading and unloading. Future work on this topic will involve using a high speed camera and a piezostack actuator to characterize the contact process more rigorously, and will be compared with improved models that implement a friction boundary condition, viscoelastic material properties, and a Dugdale-Barenblatt cohesive zone model to simulate the contact and crack propagation processes.



Figure 4.1: The graph shows how the tip of the fiber relaxes back to its initial configuration after being bent due to large compressive loads. The micrographs show the position of the tip at the beginning (A) and end (B) of the graph's data range.

## **Anisotropy in Micromanipulators**

In our investigations of pick-and-place micromanipulation we found that the contact area of the tip and edge were critical parameters in enabling control of attachment strength. We showed that changing the tip shape had an effect on how the angled pillar behaved during

the contact process, and we hypothesize that modifying the side-walls will likewise affect the contact process. A possibility is to locally modify the stiffness of the pillar through electron beam irradiation or through metal deposition. Both approaches have been demonstrated on adhesive microstructures before [145, 183], and might be a useful in applications for micromanipulation presented here. The main goal is to create a non-adhesive edge and sidewall such that when the pillar loses tip contact and makes edge or side contact the attachment force will be minimized.

## **Micromanipulation of Non-Rectilinear Parts in Parallel**

Until now, our and our colleagues' demonstrations of micromanipulation using adhesive microstructures have been for parts which are highly regular and rectilinear. Although most microfabricated and fragile devices are very regular shapes, they are not all flat, rectangular parts. We hypothesize that the principles of rough-surface adaptability observed in structured adhesives can be applied to conforming to and picking up irregular parts, but that it will require structures much smaller than the part and/or hierarchical structuring. Additionally, we hypothesize that addressing the difficulty of picking-and-placing irregular parts will lead to improved capabilities in handling many parts in a parallel (see Figure 4.2). These improvements will advance the demonstrated micromanipulation capabilities of gecko-inspired adhesives and be a significant step towards industrial application.

## **Automation of Micromanipulation**

Perhaps the single biggest improvement that can be made to prepare the manipulator for industrial applications is to integrate it in an automated system. This requires implementation of visual tracking of the micromanipulator and parts as well as intelligent failure recovery behaviors, such as clearing away damaged parts and accurately identifying when parts are not well attached to the manipulator. Additional degrees of freedom actuation is also important to automatically align the micropillar to the part, since we have observed that even slight misalignment can significantly degrade attachment strength (Figure 4.3).



Figure 4.2: This schematic represents the contact process for the next generation micromanipulation system. (a) Arrays of micropillars smaller in size than the pars to be manipulated are brought into contact before (b) the tips are engaged by shearing the adhesive array and (c) the parts are lifted off the donor substrate. Either (d1) shear displacement control or (d2) vertical displacement control is used to (e) release the parts to the receiver substrate.

## 4.2.3 Developing and Improving Self-Cleaning Adhesives

## Characterize Principles of Self Cleaning as it Relates to All Regimes of Structured Adhesives

We have proposed regimes of self-cleaning that were observed in micropillars with mushroom tips made of polyurethane with an elastic modulus of 10 MPa, but structured adhesives cover a range of sizes down to the nanoscale and up to the milliscale, and elastic moduli that are up to two orders of magnitude stiffer or softer. We hypothesize that our proposed regimes of self-cleaning are valid for all regimes of structured adhesives and that different sizes and stiffnesses of structures will clean in different ways. Furthermore, we hypothesize that hierarchical adhesive structures actually combine multiple regimes of self cleaning. What is unclear is at what critical length scales or stiffnesses the regimes transition; further characterization of these parameters will lead to developing universal principles that will help in the design of the next generation of gecko-inspired adhesives.



Figure 4.3: This graph shows how with even slight misalignment, the adhesion force of an array of micropillars can be reduced almost by half.

## Self-Cleaning of Real-World Contaminants

Our analysis, and, in fact, almost all studies found in the literature, of self-cleaning was conducted in a laboratory environment with relatively well characterized spherical particles. For self-cleaning adhesives to have a real impact, they need to be robust to all forms of contaminants. This requires a characterization of the most common contaminants and extensive investigation into what principles of self-cleaning are universal for all sizes and structures of dirt particles.

## **Implement Hierarchical Structures to Act as Particle Traps**

The feet of geckos have flaps of tissue covered in tissue and separated from each other. These flaps, called lamellae (Figure 4.4), may effectively act as particle traps, allowing some particles to roll off of the adhesive setae and aid in adhesion recovery. Implementing a similar structure in synthetic adhesives may be a key to creating self-cleaning adhesives.



Figure 4.4: An SEM image of the lamellae adorning the toes of geckos. The results from our selfcleaning research suggest that lamellar structures may actually aid in adhesion recovery by leaving a space for dirt particles to be trapped, away from the tips of the adhesive structures. (Copyright Cliff Mathisen, FEI Company)

#### Non-dimensional Parametric Analysis of Self-Cleaning

The results of our self-cleaning study revealed a relationship between particle size and the ability of a structured adhesive to recover adhesion. We also found that the mechanics by which an array of structures self-cleans was also related to the particle size. However, for these results to have a broad impact on the field of gecko-adhesives, there must be a parametric relationship in place that informs optimized design. Therefore we propose that future work on this topic should focus on a systematic analysis of what geometric parameters, such as pillar height, length, and pitch, act as the critical dimensions that determine the mechanics and degree to which self-cleaning occurs. A non-dimensional analysis combining geometric parameters, with loading conditions and material properties may reveal a universal relationship that is equally relevant to the gecko's foot as it is to the synthetic gecko-adhesives made in the lab.

## **Adhesion Recovery in Climbing Robots**

We have presented Waalbot II, a climbing robot that used gecko-inspired adhesives for attachment (see Appendix A). Waalbot was capable of obtaining information about its climbing state in the world; it could sense the adhesion force on each of the 6 feet by using only two force sensors mounted on the tails. Using the force sensor data, the robot was able to regain adhesion lost due to fiber degradation, which it did by rocking its feet to be able to continue climbing safely for a prolonged period of time. We hypothesize that the adhesion recovery ws due to the structured adhesives conforming to dirt and roughness to allow clean patches of micropillars to contact the climbing substrate. Our recent discoveries about the regimes of self-cleaning in structured adhesives suggests that shearing the adhesive pads will help recover adhesion and actively clean the adhesive feet. Implementing these principles to climbing robots will greatly improve their utility and practicality because they will be able to climb dirty surfaces without loss of adhesion.



## Waalbot II: Adhesion recovery and improved performance of a climbing robot using fibrillar adhesives

This appendix represents a work published in collaboration with Dr. Michael P. Murphy (lead author), Casey Kute (co-author) and Prof. Metin Sitti (primary investigator) [22].

Waalbot was first introduced in Murphy et al. using flat elastomers to climb [155]. The improvements presented in this appendix build upon the basic design principles of the robot to increase capabilities. One major change was the utilization of dry fibrillar gecko-inspired adhesives onto Waalbot II, initially introduced in [156], with further testing and performance improvements presented in this paper. Since the adhesion ability of the footpads increased due to the fibrillar adhesives' performance, a better passive peeling mechanism was implemented to increase reliability and mobility. Waalbot II is now equipped with force sensors that allow for monitoring of the adhesive's performance. Waalbot II, while climbing, autonomously performs actions to regain adhesion and prevent detachment from climbing surfaces, an action inspired by animals that use sensory feedback to determine adhesion strength and prevent detachment by changing their climbing gaits when adhesion is low [184]. Length scale optimization was investigated to compare the factor of safety of this climbing robot using synthetic structural adhesives to the biological analogs found in nature [26]. The chassis design of the robot was also changed to include two tails for

stability and surface adaptation while climbing. Waalbot II also follows paths as generated by a motion planner to traverse complex 3D environments. The chasis design is outside the scope of this appendix, but may be found in the original work [22].

## A.1 Introduction

Animal mobility far exceeds the capabilities of mobile robots in terms of agility, robustness, and terrain flexibility. Climbing animals are able to navigate complex, unstructured 3D environments while scaling a wide variety of surfaces, such as trees, rocks, and in the case of geckos and many insects, smooth vertical and inverted surfaces. The gecko is able to climb on smooth surfaces by exploiting surface contact forces, such as *van der Waal's* forces, between small hair-like structures on the feet and the climbing surface [37]. In addition to demonstrating advanced agility capabilities, geckos have been shown to utilize their tails as an emergency fifth leg to prevent falling after sensing a loss of adhesion [184]. Similar emergency behaviors are common among climbing animals, as the consequences of a fall can be deadly. Recent advances in robot mobility have resulted in climbing robots that scale vertical surfaces using various attachment mechanisms. A similar sensing and recovery mechanism to that of the animal tail for climbing robots could prove useful to prevent unwanted detachment from climbing surfaces.

In addition to climbing robots using attachment mechanisms such as grasping with claws, spines, or grippers [185, 186, 187, 188, 189], magnetic clamping [190, 191, 192, 193, 194], pressure differential by suction cups [195, 196, 197, 198, 199, 200, 201] or scanning suction cups [202, 203, 204, 205, 206, 207], and electroadhesion [208, 209], synthetic dry fibrillar adhesives are starting to be utilized as attachment mechanisms for biologically-inspired climbing robots. Recent advances in synthetic fibrillar adhesive technology, such as high adhesion from carbon nanotube arrays [123, 125, 151, 152, 168], geometric fiber tip control [70, 76, 77, 88], directional adhesion [5, 9, 141, 144], and hierarchical structures [4, 5], have increased the performance of these materials to the point where they can be successfully implemented as attachment mechanisms in climbing robots. Daltorio et al. outfitted their Mini Whegs robot with mushroom tipped synthetic dry adhesives and demonstrated climbing smooth vertical glass [189]. Similarly, Kim et al. constructed a



Figure A.1: a) Photograph of Waalbot with components labeled and an inset of an SEM image of the gecko-inspired dry fibrillar adhesives used in the footpads; b) Details on naming conventions used for the leg and its components.

legged robot resembling a gecko, which uses directional polymer adhesives to climb up smooth surfaces [137]. Then, Santos et al. showed climbing on slightly underhanging surfaces [210] and Asbeck et al. showed successful climbing on rough surfaces using hierarchical adhesives [158].

Waalbot II (Fig. A.1), named after the *van der Waal's* forces it dominantly uses to climb, is a small-scale agile wall climbing robot able to climb on planar surfaces of any orientation using flat adhesive elastomers or fibrillar adhesives for attachment [155]. The essential morphology and force transfer concept of the Waalbot design was first seen in a robot created by iRobot, named Mecho-Gecko, which had a tri-leg design that was used to passively peel pressure sensitive adhesives off the climbing surface while climbing [39]. However, Waalbot II uses flat or fibrillar elastomer adhesives as the attachment material and has steering and surface transitioning abilities. Using two actuated legs with rotary motion and two passive revolute joints at each foot, this robot can climb and steer in any orientation. The passive revolute ankle joints allow the feet to pivot forward to remain in contact with the surface during stepping (Fig. A.2). An elastic is used to passively return the foot to the forward position after each step. Due to the minimalistic and compact design, a high degree of miniaturization is possible. The robot carries on-board power,

computing, and wireless communication, which allows for semi-autonomous operation. The average power consumption for Waalbot is 2.4 W for an average vertical climbing speed of ~5 cm/s (0.5 body lengths/s). Waalbot climbs using synthetic fibrillar adhesives or a pressure sensitive dry adhesive elastomer and is also able to make sharp turns [155] and plane transitions, including floor-to-wall, wall-to-wall, and wall-to-ceiling transitions. The robot is also intended to climb real-world surfaces that are not completely smooth, such as a painted wall or wood surface.



Figure A.2: CAD diagrams showing the stepping process for a forward step (leg rotating clockwise in image). a) Two feet (A and B) are in contact; b) Foot A is peeled from the surface; c) Foot A releases from the surface and the robot begins to move forward; d) Foot C rotates closer to make contact with the surface; e) Foot C achieves contact with the surface and now foot B is the rear foot. The process continually repeats for forward movement.

Waalbot was first introduced in Murphy et al. using flat elastomers to climb [155]. The improvements presented in this work build upon the basic design principles of the robot to increase capabilities. One major change was the utilization of dry fibrillar gecko-inspired adhesives onto Waalbot II, initially introduced in [156], with further testing and performance improvements presented in this paper. Since the adhesion ability of the footpads increased due to the fibrillar adhesives' performance, a better passive peeling mechanism was implemented to increase reliability and mobility. Waalbot II is now equipped with force sensors that allow for monitoring of the adhesive's performance. Waalbot II, while climbing, autonomously performs actions to regain adhesion and prevent detachment from climbing surfaces, an action inspired by animals that use sensory feedback to determine adhesion strength and prevent detachment by changing their climbing gaits when adhesion

is low [184]. The chassis design of the robot was also changed to include two tails for stability and surface adaptation while climbing. Waalbot II also follows paths as generated by a motion planner to traverse complex 3D environments.

Length scale optimization is explored in section A.2. Waalbot II's ability to regain adhesion lost while climbing due to fiber degradation is discussed in section A.3. Implementation details and specifications for a motion planner to aid in the exploratory climbing abilities of Waalbot II are also discussed in section A.3. Finally, conclusions and future directions are reported in section A.4.



Figure A.3: Still image frames from a video of the robot climbing from the floor (a) to the wall (b,c,d), transferring to the rear wall (e,f), and then transferring to the ceiling (g,h) of an acrylic cube. The robot path is illustrated in (a) with an overlay. A weight is hung in the top corner for reference to show that the direction of gravity is down.

## A.2 Length Scale Optimization

The same physical laws govern the behaviors of animals and robots of vastly varying sizes, but different forces tend to dominate at different scales. In climbing robots and animals the two most important parameters are the total adhesive area and mass, and these parameters scale differently. Given constant geometric proportions, as a climbing robot's length scale increases monotonically, its foot area increases as the square of the length and its mass



Figure A.4: a) Plot showing force data from the two tail force sensors while the robot climbs on a smooth, vertical surface; b) the robot starts out with sufficient adhesion to maintain attachment; c) On the second step, the right side loses adhesion and detaches from the wall. The robot continues moving sideways, stepping with both feet, but only the left side has sufficient adhesion and the right side continues to slip.

increases as the cube of the length. This carries a very strong implication: a climbing robot that is doubled in size will have four times as much adhesion but eight times as much mass and hence its adhesion to weight ratio will have been halved. In this section we develop an optimization model to help determine the appropriate size scale for a given payload requirement.

In developing the optimization analysis certain constants and relationships were assumed. First, the robot's geometric proportions stay constant as its size varies (isometric scaling). Additionally, a constant small mass of 10 g, for all robots, was included as the weight of the electronics and sensors. Another constraint was applied to the maximum available adhesion by limiting the adhesion to the amount that could be pulled off by servos in the weight class related to the length scale.

The objective function of the optimization was the theoretical factor of safety of the climbing robot's adhesion, and the independent variable was the length of the robot, which was defined as the distance between the servo axle and the tip of the tail. The theoretical factor of safety is the proportion of available adhesion to the mass of the robot, meaning that a theoretical factor of safety of one represents a marginal design and less than one



Figure A.5: Simulated length scale effect on a climbing robot's theoretical factor of safety. With increasing payload masses, the optimum size of a Waalbot increases. The shaded region along the bottom is where the theoretical factor of safety is below 1. The dots represent the calculated factor of safety for various types of pad-bearing lizards as adapted from [26].

represents a robot that cannot climb. The primary purpose of climbing robots is to carry out some task, which requires carrying additional equipment, such as cameras, surfaces inspection sensors, and wireless communications hardware, so the optimization plots the theoretical factor of safety in relation to the length scale for varying payloads (Fig. A.5). The theoretical factor of safety values emerging from the optimization are artificially large because the analysis assumes ideal contact and no dynamic forces.

The optimization suggests that a larger robot will be able to carry more payload but with a smaller theoretical factor of safety, and in fact this has been observed with two different scales of Waalbot prototypes. The larger version, Waalbot II (Fig. A.1), with a length is 95.6 mm, can climb vertically and carry up to 100 g payloads, but has difficulty robustly climbing on ceilings. The smaller version (Fig. A.6), with a length of 56.1 mm, is able to climb and transition easily at all surface orientations, but requires power and electronics to be off-board and also has the problem of twisting off from the wall due to the

single tail design. Video snapshots of the small prototype climbing inside an acrylic cube in Fig. A.6 illustrate the prototype consecutively climbing down a wall (a), transitioning from the wall to the floor (b), crawling across the floor (c), performing a floor-to-wall transition (d), climbing a vertical wall (e), transitioning from wall-to-wall (f), steering on a wall (g), transitioning from the wall to the ceiling (h), performing inverted steering (i), and successfully climbing while inverted (j). These agility demonstrations indicated that both scales have good performance and can achieve the performance objectives outlined in the introduction. To increase the performance of the smaller scaled robot, the two tail design should be implemented to mitigate any synchronization problems.



Figure A.6: Small-scale Waalbot climbing inside an acrylic cube with 30 cm sides demonstrating: a) climbing down a wall; b) transitioning from a wall to the floor; c) crawling across the floor; d) floor-to-wall transition; e) vertical wall climbing; f) wall-to-wall transition; g) steering on a wall; h) wall-to-ceiling transition; i) inverted steering; j) inverted climbing.

## A.3 Advancements for Semi-Autonomous Control

In order to move towards the development of an autonomous climbing robot, certain issues facing the current Waalbot II design were addressed. By using dry fibrillar adhesives and passive peeling, Waalbot II can climb on a variety of surfaces. However, different surface conditions and the degradation of the adhesive forces can lead to catastrophic failure. To address these limitations, Waalbot II exploits the force transfer design, by means of a rocking maneuver, to regain adhesion when a loss of adhesion is detected. Additionally, Waalbot II has kinematic constraints, such as its inability to step backwards and side step, that require foresight in climbing so that it does not get stuck. To help Waalbot II navigate

its environment safely, a motion planner that takes into consideration the robot's unique kinematic constraints was implemented.

## A.3.1 Adhesion Recovery

One way to to increase the robustness of Waalbot II's climbing ability is to introduce adhesion sensing and recovery, which will allow the robot to regain adhesion lost due to a misstep, or contaminated fibers. Animals that are skilled at climbing smooth vertical surfaces are capable of sensing how well they are adhered to the surface. For example, if the gecko senses loss in adhesion in the front feet, it will use its tail to counteract the pitchback moment and regain adhesion [184]. Our goal was not to mimic the actions of the animals, but to utilize the principles behind their robust climbing abilities. Therefore, adhesion sensing was implemented on Waalbot using force sensors on each tail, which directly measures the adhesive force of the corresponding foot through the quasi-static force transfer equations presented in [155].

A control scheme was implemented such that when the force of either foot dropped below a certain threshold value the system began an adhesion recovery motion. From experimental results, it is shown that the adhesion recovery is effective and leads to a more robust climbing system. The recovery system takes the tail force as the input and compares it to an empirically-defined threshold force, which can be obtained by running experiments on the desired climbing surface. If the tail force is lower than the safety threshold, the system initiates a rocking maneuver, which will be presented in detail. After the recovery, the robot continues to climb normally until the tail force drops below the threshold again when the rocking maneuver is again initiated.

#### **Adhesion Sensor Selection**

Adding force sensing to the footpads of the robot would be a challenging task due difficulties of adding instrumentation to the six feet which are subject to continuous rotation of the leg mechanisms. Instead, a force sensor at the end of each of the robot's tails was added. Only two sensors are required to capture the adhesion information about the force transfer of all of the feet, and the tails are more easily instrumented due to their proximity to the



Figure A.7: Free body diagram showing the forces present during a forward step on a surface at angle  $\psi$  where the front foot is pressed against the surface and the rear foot is being peeled.  $F_{RX}$  and  $F_{FX}$  are the rear and front forces, respectively, in the X direction.  $F_{RN}$  and  $F_{FN}$  are the rear and front forces, respectively, in the normal ,Y, direction.  $F_T$  is the tail force, while W is the weight of the robot acting on the center of gravity.

electronics and their static configuration. These sensors are able to capture the same force information as footpad sensors would because the tail is used as a support to help detach the feet during stepping. During the force transfer from the rear feet to the front feet, the force on the tails are directly proportional to the pull-off force of the detaching foot [155]. If the adhesion force is as strong, or stronger than the gravity force, the adhesion can be measured at any surface orientation, since the robot always uses the tail to transfer forces while taking a step. The relationship can be obtained by solving for the tail force as a function of other known parameters, such as robot weight and geometry, using Fig. A.7 and assuming negligible tail friction as

$$F_{FY} = \frac{F_T[L + \frac{d_{step}}{2}] + Wcos(\Psi)[\frac{d_{step}}{2} - L_{xcg}] + Wsin(\Psi)[-2L_{ycg}]}{d_{step}}$$
(A.1)

where  $F_{FY}$  is the normal force on the front food,  $F_T$  is the tail force,  $d_{step}$  is the distance between the ankles of two feet, W is the robot weight,  $\Psi$  is the climbing surface angle,  $L_{xcg}$ and  $L_{ycg}$  are the distances from the center of gravity, where the weight acts, to the center of the servo horn and the climbing surface, respectively. To have a high safety factor, the

gravity component of the tail force is minimized by having the robot body close to the wall, which means a small  $L_{ycg}$ . This equation is only accurate for climbing up or down a surface at any orientation. If the robot climbs sideways, the equation would need to be modified to reflect the imbalance in the distribution of the weight between the tails.

Piezoresistive force sensors (0.2" Interlink FSR) were chosen, due to their small mass and size, and ease of integration. These sensors were added to the electronics in a voltage divider configuration. The resistor value was selected to optimize the range of the output voltage from the sensor over the force range that the robot is able to produce at the tail (0-4 N), determined using the value of the maximum torque output from the servo and the moment arm between the servo and the tip of the tail. Tests were then run using a load cell and a motorized stage with applied force values from 0-4 N and the sensor was characterized for linearity, repeatability, and drift. Although the response was nonlinear, the sensor had acceptable repeatability, and negligible drift.

#### **Adhesion Level Sensing and Recovery**

The tail force sensors were integrated into Waalbot II, and software was written to record and report the maximum tail force sensed during each step. The maximum tail force occurs right at pull off from the surface, however, this is a difficult event to catch as it is rapid. To increase the chances of capturing the most accurate reading, the force sensors are continuously polled, at the limit of the microprocessor and program code, and the maximum of the set of readings is taken as the maximum tail force. An instrumented Waalbot II was tested with magnetic footpads on a metal surface to investigate the reliability of the adhesion sensing. The adhesion from the magnetic feet was observed to remain constant over many robot steps, indicating that the force sensors functioned as intended.

To regain adhesion, Waalbot II brings two feet on the side where adhesion was lost into contact with the surface, and then commands the motors forward and backward at a constant torque value without allowing either foot to completely detach. We propose that pressing back and forth between the attached feet, using the same force to press down on the feet each time, engages increasingly more fibers as they are able to avoid dirt particles and thus a higher effective contact area is gained, which increases the adhesion (Fig. A.8).

The rocking motion applies normal forces to preload the front and rear feet without



Figure A.8: Possible mechanism of adhesion increase during rocking motion: a) Illustration showing a piece of dirt that inhibits surrounding fibers from engaging with the surface; b) More fibers can engage with the surface when repeatedly loaded and unloaded during rocking maneuvers.

letting the other foot detach from the surface by alternating the direction of the motor and only allowing a small rotation of the leg. To test the hypothesis that rocking at a constant torque setting, will increase the adhesion, an experiment was run. The robot, with fibrillar adhesive footpads, was placed on a surface with a 10 *lb* load cell (MLP-10; Transducer Techniques Inc.) under each foot on one side (Fig. A.9). The other side of the robot and both tails were supported by a stationary surface. The voltage readings from both of the load cells, which represent the force on the front and rear foots separately, were recorded through a data acquisition board (NI PCI-6259; National Instruments). The robot then performed the rocking maneuver and the forces were recorded. As seen in Fig. A.10, the adhesive force increases with an increase in the number of rocking motions.



Figure A.9: Illustration showing the setup to examine the effect of a rocking motion using constant preload.

To test the adhesion threshold value in situ, the robot was commanded to climb vertically on an acrylic surface that had surface imperfections, and forces were recorded until the robot fell from the surface. The adhesion values recorded before the robot detached from the surface were taken as the safety threshold for the adhesion and was empirically set to be 0.325 N. The threshold value is dependent and needs to be updated if the environmental conditions change, which includes continued degradation of the fibers. Increasing the life-time of the adhesive and using more accurate force sensors would decrease the sensitivity of the threshold value.



Figure A.10: Experimental results showing the increase in adhesion when the number of rocking maneuvers is increased, when rocking using a constant preload.

The recovery motion ceases once 5 rocking cycles have been completed, which experiments show a sufficient adhesion recovery to continue climbing (Fig. A.10). As seen in Fig. A.11, the adhesion recovery action begins once the force sensor value drops below the threshold, 0.325 N. After the adhesion recovery event, the robot regains the adhesion during the subsequent steps (Fig. A.11).

## A.3.2 Motion Planning

There is significant interest in utilizing climbing robots for inspection and surveillance applications. In motivating the design of a planning algorithm, we considered Waalbot II's use in a man-made environment with the benefit of external hardware for environment modeling and robot localization. Our implementation assumes the use of VICON motion capture cameras for modeling and localization tasks as presented by Halaas et al. [211] and



Figure A.11: Plot showing the force on the feet over many steps as well as the increase in adhesion due to regain adhesion events. When the force on the tail sensor drops below 0.325 N, the adhesion regain event is triggered and the adhesion then increased on the subsequent step.

Saad et al. [212]. The critical aspect of the system is that it generates a tessellated 3D model of the environment and robot pose and location which are then fed into our algorithm. Our planner begins by decomposing this 3D environment into locally flat 2D regions. We implement a hierarchical algorithm to find a multi-region solution trajectory across the connected locally flat regions. This implementation was developed independently, but is similar to the approach taken by Morisset et al. and Bretl et al. [213, 214].

The upper level planner generates a graph of valid configurations along the boundaries between regions, or more conveniently, waypoints. Then, using Euclidean distance heuristics and A\* search on the graph, the upper level planner chooses the lowest cost trajectories between waypoints. The trajectories across a single 2D region are then updated by the lower level planner, which functions as a primitive planner, wherein a separate A\* algorithm is used to search a discrete state space. The state space is expanded by generating new states of all possible motion primitives from the lowest cost state in the priority queue at each iteration. The upper level planner updates the trajectory costs in its graph according to the lower level planner's actual costs and continues its search, only running the more computationally intensive lower level planner as needed. When the upper level
#### A. Waalbot

planner has completed its search and found the optimal path it creates a composite trajectory from the multiple lower level planner trajectories, each across a single locally flat 2D region (Fig. A.12). A video showing a solution trajectory being followed by Waalbot II can be seen in Extension 2. The motion planning is conducted off-board and the motion commands are sent to the robot wirelessly from a controller computer.



Figure A.12: Overview of the 2-level motion planner: a) Waypoints are generated along transitionable plane intersections and connected; b) Trajectories are generated to plan a path between the waypoints. The relative orientations of the wall, floor, and ceiling is arbitrary.

### A.4 Conclusion

The final wireless robot prototype demonstrates high agility by performing difficult maneuvers, such as steering with a small turning radius, and transitioning between surfaces of different orientations, including floor-to-wall, wall-to-wall, and wall-to-ceiling transitions, while climbing with dry fibrillar adhesives. Climbing and steering on inverted smooth surfaces, and climbing and steering on non-smooth surfaces, such as wood, have been demonstrated. The new design also exhibited the robot's ability to carry a payload that is more than the bodyweight of the robot. To the authors' knowledge, no other dry adhesives based climbing robot can perform sharp turns, plane transitions, inverted climbing, and climb on non-smooth surfaces. In this paper, we showed and validated improvements to Waalbot's mechanical design. With the inclusion of fiber footpads, the passive peeling feet were necessary, and able to lower power consumption, increase climbing speed, and robot dependability. The new tail design, which included two tails and a passive pin joint, prevented unwanted crossbody movements and can be applied to other climbing robots to increase their reliability. Through an analysis of the scaling equations governing the robot design, an understanding of the robot length and its subsequent ability to carry a payload of a certain mass with a theoretical factor of safety was also explored. The results were then validated by building and testing two different sized Waalbots.

The robot is now capable of obtaining information about its climbing state in the world. The robot is capable of sensing the adhesion force on each of the 6 feet by using only two force sensors, which are mounted on the tails. From the force sensor data, the robot is then able to regain adhesion lost due to fiber degradation by rocking to be able to continue climbing safely for a prolonged period of time. A two-level motion planner was developed and implemented such that transitions between locally flat regions were identified using the upper level planner and the specific robot trajectory was planned using an A\* search. Results show that the robot's trajectories closely match the plannet trajectories.

One of the major disadvantages of this robot design is that there is very little redundancy with respect to adhesion failure. To maximize the agility of the robot, increasing its speed and decreasing the turning radius, redundant attachment points were left out of the design. Much of the time, there are only two feet attached to the surface. As the adhesives gather dust and other contaminants, their performance degrades quickly. Therefore, these adhesives are currently not suitable for dirty outdoor environments, walking across indoor floors, or for long term tasks. Furthermore, the possibility of adhesion failure during a plane transition when improper foot placement occurs is a dangerous flaw for a climbing robot, but could be mitigated by adding additional passive degrees of freedom in the foot.

Future work includes further miniaturization of the robot for improved performance. As the required on-board electronics, such as wireless communications, sensing, and control become available in smaller packages, the robot should be easily scalable, at least to the small-scale (15 g) size of the prototype from section A.2. Other improvements include the ability to walk on dirty ground without contaminating the fiber footpads. Potentially, the

robot could flip itself over simply by running the legs in reverse to walk on the back-sides of its ankles. This improvement would also enable the robot to self-right in the case of a fall where it lands on its back. Further improvements in fiber adhesives would include addressing degradation issues to allow for more reliable adhesion and adding directional adhesion to allow the robot to be even more power efficient in the removal of the feet from the climbing surface. The tail and body design can be further improved to allow to robot to traverse external transitions and thus increase the environmental space in which the robot can operate.



# Interfacial Contact Patch Visualization through Interferometric Microscopy

This appendix covers the theory and implementation of utilizing interference microscopy to visualize the area of contact of an interface.

The basic principle is that light reflecting from surfaces separated by a thin film of lower index of refraction medium will interfere constructively and destructively depending on the thin film thickness (Figure B.1). Since the Newton's rings are related to the separation distance of the contacting surfaces, it is possible to count the number of rings starting from the center of the dark contact patch, and calculate the gap [215]. By utilizing monochromatic green light, the wavelength of the light is fixed and the separation distance can be calculated as

$$\delta = n\left(\frac{1}{2}\lambda\right) \tag{B.1}$$

where *n* is the ring number (with the central dark region being counted as the  $0^{th}$  ring), and  $\lambda$  being the wavelength of the light (546 nm in our contact visualization experiments). Although this equation is essentially discretized, it is possible to directly measure the intensity of the light and create a continuous function of the gap thickness in terms of light intensity and lateral distance from the center of contact.



Figure B.1: (a) Schematic of the classic experiment to visualize Newton's rings [27]. (b) The fringes are a result of interference of the reflected light from the planar and hemispherical surfaces. The center of the dark band where destructive interference is seen indicates a region where the two surfaces are separated by an integer number of wavelengths,  $n\lambda$ . The center of the light bands where constructive interference is seen occurs where the surfaces are separated by some number of half wavelengths,  $\frac{n}{2}\lambda$ .



## Details of SU-8 Photolithography

This appendix covers the details of SU-8 photolithography in Carnegie Mellon's Nanofab clean room.

Fresh SU-8 2050 for structural layer, all procedures are for 100  $\mu$ m thickness unless otherwise noted.

#### Wafer Clean

- 1. Clean new wafer in wafer rinser/cleaner
- 2. Dry with N2 before pouring SU-8

#### **HMDS Spin**

- 1. 500rpm for 30s
- 2. 2000 rpm for 30s

#### SU-8 Spin

- 1. Hold the wafer in your non-dominant hand and the open bottle of SU-8 in your dominant hand
- 2. Pour the SU-8 in a puddle near the edge,
  - (a) tip the bottle up and rotate slowly so as to minimize streamers of SU-8

- (b) "cut" the last string of SU-8 against the edge of the wafer as you pull the bottle away
- 3. Slowly rotate the wafer so as to flow the SU-8, covering as much of the wafer as possible without spilling over the edges.
- 4. Center wafer on the spinner chuck using the appropriate tool (wafer-holder-chuck-centerer)
- 5. Spin according to the recipe
  - (a) 500 rpm for 10 s (should see that everything is covered)
  - (b) 1600 rpm for 30 s to achieve  $100 \ \mu m$  thickness (SU-8 2050).
    - i. Hold two q-tips vertically, near the spinning wafer to draw away SU-8 as it is flung off of the wafer
- 6. Do NOT clean the backside with a q-tip dipped in acetone while still on spinner
- 7. Remove from spinner and continue cleaning any large bits of SU-8, keeping the wafer as level as possible.

#### Soft Bake

- 1. Ensure the hotplate is level
- 2. Place the wafer on the metal plate on top of the ceramic hot plate at room temperature
- 3. Ramp to  $70^{\circ}$ C (takes about 10 minutes)
  - (a) Hold for 5 minutes
- 4. Ramp to 80°C
  - (a) Hold for 5 minutes (start timer when temperature hits  $78^{\circ}$ C)
- 5. Ramp to 90°C
  - (a) Hold for 5 minutes (start timer when temperature hits 88°C)

- 6. Ramp to 100°C
  - (a) Hold for 17 minutes (start timer when temperature hits  $98^{\circ}$ C)
- 7. Turn off hotplate let the wafer cool to room temperature with hotplate heat mass

#### Exposing

- 1. Set up the MA-56 exposer (SEE the operating guide below) with the contact mask and cooled down wafer
- 2. Expose for 90s for 100 µm thickness
  - (a) The MA-56 is currently set to  $7.2 \text{ mW/cm}^2$
  - (b) Microchem recommends 150-215 mJ/cm<sup>2</sup> for 45-80  $\mu$ m which comes to 20-29 s

#### **Post Exposure Bake**

1. Follow the same procedure as soft bake (above)

#### Developing

- 1. Fill a Teflon petri dish with SU-8 developer
  - (a) Place the cooled down wafer into the dish
- 2. Allow to develop for up to 20 minutes (for 100 µm thickness)
  - (a) Agitate lightly by rocking the dish or by lifting the wafer repeatedly with a tweezer
- 3. Remove wafer from dish and rinse with IPA for 10 seconds
  - (a) If white film forms, it's underdeveloped
    - i. Rinse the IPA residue with DI water
    - ii. Dry with  $N_2$  or air VERY carefully so as not to damage the structure
  - (b) Place the wafer back into the developer, return to step 2a

4. Dry with compressed  $N_2$ 

#### Hard Bake

1. No hard bake

#### MA-56 UV Exposer Operating Guide

- 1. Turn on the three gas valves behind the machine
- 2. Turn on the lamp power switch
  - (a) Press and hold the Lamp button until the lamp light comes on
  - (b) Start timing yourself (the time the lamp is on is what you will put in the log book)
  - (c) Wait for the display to show the lamp has warmed up to 275 W
- 3. Turn on the Main Power switch
  - (a) Press the Red "W/O Cass Load" button
  - (b) Press the White "Center Position" button
- 4. Load the mask into the mask holder
  - (a) NOTE: it should be BOTTOM side UP
  - (b) Press the White "Mask Load" button
  - (c) Make sure the mask is securely vacuumed to the holder
- 5. Load your wafer onto the wafer holder
- 6. Turn mask holder right-side up and slide onto the rail above the wafer
  - (a) Press the white "Maskh. Clamp" button
- 7. Press the white "Start Alligner" button
  - (a) If you hear a beeping, then there is most likely SU-8 on the back of your wafer which is preventing the machine from making a strong vacuum seal.

- (b) SOLUTION: get a clean junk wafer and place it on the wafer holder, laying your wafer on top of it. This will prevent you from doing very fine alignments.
- 8. Set your exposure timer
  - (a) NOTE: that the rightmost digit is 1/10 of a second.
  - (b) For example: 0300 is actually a 30 second expose.
- 9. Press the White "Align" button on the joystick, the "Expose" light should come on
  - (a) Press the Red "Expose" button on the joystick.
  - (b) Turn away so as to not expose your retina to UV light
- 10. After youre done exposing:
  - (a) Press the white "Maskh. Clamp" button and remove holder from rails
  - (b) Press the white "Mask Load" button and remove the mask from the holder
  - (c) Remove your wafer(s) from the wafer holder
  - (d) Turn off Main Power switch
  - (e) Turn off Lamp Power switch
  - (f) Make note of how long the lamp was on, and write it in the log book
  - (g) Turn off the PV and CA lines behind the machine
  - (h) Leave the Nitrogen line on for 10 more minutes before turning it off in order to cool off the lamp
  - (i) If you leave the Nitrogen on you will be charged an extra fee

### References

- K. Autumn and W. Hansen, "Ultrahydrophobicity indicates a non-adhesive default state in gecko setae," *Journal of comparative physiology*. A, vol. 192, pp. 1205–12, Nov. 2006. (document), 1.1, 1.2
- [2] R. Ruibal and V. Ernst, "The structure of the digital setae of lizards.," *Journal of morphology*, vol. 117, pp. 271–93, Nov. 1965. (document), 1.1, 1.2, 1.4.1, 3.1
- [3] K. Autumn, C. Majidi, R. E. Groff, A. Dittmore, and R. Fearing, "Effective elastic modulus of isolated gecko setal arrays," *Journal of Experimental Biology*, vol. 209, pp. 3558–3568, 2006. (document), 1.1, 1.4.3
- [4] M. P. Murphy, S. Kim, and M. Sitti, "Enhanced adhesion by gecko-inspired hierarchical fibrillar adhesives," ACS applied materials & interfaces, vol. 1, pp. 849–55, Apr. 2009. (document), 1.1, 1.4.1, 1.4.3, 2.1, A.1
- [5] H. E. Jeong, J.-K. Lee, H. N. Kim, S. H. Moon, and K. Y. Suh, "A nontransferring dry adhesive with hierarchical polymer nanohairs.," *Proceedings of the National Academy of Sciences of the United States of America*, vol. 106, pp. 5639–44, Apr. 2009. (document), 1.1, 1.4, 1.4.1, 1.4.1, 1.4.1, 1.4.2, 1.4.3, 1.5.1, 1.5.1, 1.7, 2.1, 2.2.1, 2.2.2, 2.4.3, 3.1, A.1
- [6] K. Autumn, "Gecko Adhesion: Structure, Function, and Applications," *MRS Bulletin*, vol. 32, pp. 473–478, Jan. 2007. (document), 1.2.3, 1.2, 3.1, 4, 4.1.4
- [7] K. Autumn, M. Sitti, Y. A. Liang, A. M. Peattie, W. R. Hansen, S. Sponberg, T. W. Kenny, R. Fearing, J. N. Israelachvili, and R. J. Full, "Evidence for van der Waals adhesion in gecko setae," *Proceedings of the National Academy of Sciences of the United States of America*, vol. 99, pp. 12252–6, Sept. 2002. (document), 1.2.1, 1.2, 1.4.1, 2.1

- [8] K. Autumn, A. Dittmore, D. Santos, M. Spenko, and M. Cutkosky, "Frictional adhesion: A new angle on gecko attachment.," *The Journal of Experimental Biology*, vol. 209, no. Pt 18, pp. 3569–79, 2006. (document), 1.2, 1.2.1, 1.2.3, 1.2, 2.1, 2.2.3
- [9] M. P. Murphy, B. Aksak, and M. Sitti, "Gecko-inspired directional and controllable adhesion.," *Small*, vol. 5, pp. 170–5, Feb. 2009. (document), 1.2, 1.3.2, 1.3.3, 1.4, 1.4.1, 1.4.1, 1.4.1, 2.1, 2.2.3, 3.1, A.1
- [10] M. K. Kwak, H.-E. Jeong, and K. Y. Suh, "Rational Design and Enhanced Biocompatibility of a Dry Adhesive Medical Skin Patch," *Advanced materials*, vol. 23, pp. 3949–3953, July 2011. (document), 1.2, 1.3.2, 1.5.2, 1.8, 3.1, 4
- [11] W. R. Hansen and K. Autumn, "Evidence for self-cleaning in gecko setae.," *Proceedings of the National Academy of Sciences of the United States of America*, vol. 102, pp. 385–9, Jan. 2005. (document), 1.2.1, 1.2, 2.1, 3.1, 3.3, 3.4, 4, 4.1.4
- [12] E. Arzt, S. Gorb, and R. Spolenak, "From micro to nano contacts in biological attachment devices.," *Proceedings of the National Academy of Sciences of the United States of America*, vol. 100, pp. 10603–6, Sept. 2003. (document), 1.2, 1.2.1, 1.2.3, 1.3.1, 1.3, 3.1
- [13] A. K. Geim, S. V. Dubonos, I. V. Grigorieva, K. S. Novoselov, A. A. Zhukov, and S. Y. Shapoval, "Microfabricated adhesive mimicking gecko foot-hair," *Nature materials*, vol. 2, pp. 461–3, July 2003. (document), 1.4, 1.4.2, 2.1
- [14] S. Gorb, M. Varenberg, A. Peressadko, and J. Tuma, "Biomimetic mushroom-shaped fibrillar adhesive microstructure," *Journal of the Royal Society Interface*, vol. 4, pp. 271–275, Aug. 2007. (document), 1.3.1, 1.3.2, 1.4, 1.4.1, 2.1, 3.1, 3.3, 4
- [15] A. Parness, D. Soto, N. Esparza, N. Gravish, M. Wilkinson, K. Autumn, and M. Cutkosky, "A microfabricated wedge-shaped adhesive array displaying geckolike dynamic adhesion, directionality and long lifetime.," *Journal of the Royal Society, Interface*, vol. 6, pp. 1223–32, Dec. 2009. (document), 1.4, 1.4.1, 1.4.1
- [16] C. Majidi, R. Groff, Y. Maeno, B. Schubert, S. Baek, B. Bush, R. Maboudian, N. Gravish, M. Wilkinson, K. Autumn, and R. Fearing, "High Friction from a Stiff Polymer Using Microfiber Arrays," *Physical Review Letters*, vol. 97, no. 7, pp. 18– 21, 2006. (document), 1.3.3, 1.4, 2.1
- [17] M. K. Kwak, H. E. Jeong, W. G. Bae, H.-S. Jung, and K. Y. Suh, "Anisotropic Adhesion Properties of Triangular-Tip-Shaped Micropillars," *Small*, vol. 7, pp. 2296–2300, June 2011. (document), 1.4, 1.4.1, 2.1

- [18] C. Greiner, E. Arzt, and A. del Campo, "Hierarchical Gecko-Like Adhesives," Advanced Materials, vol. 21, pp. 479–482, Jan. 2009. (document), 1.4, 1.4.3
- [19] S. Kim, B. Aksak, and M. Sitti, "Enhanced friction of elastomer microfiber adhesives with spatulate tips," *Applied Physics Letters*, vol. 91, no. 22, p. 221913, 2007. (document), 1.3.3, 1.4, 2.1
- [20] A. del Campo, C. Greiner, I. Álvarez, and E. Arzt, "Patterned Surfaces with Pillars with Controlled 3D Tip Geometry Mimicking Bioattachment Devices," *Advanced Materials*, vol. 19, pp. 1973–1977, Aug. 2007. (document), 1.4, 1.4.1
- [21] M. K. Kwak, C. Pang, H.-E. Jeong, H.-N. Kim, H. Yoon, H.-S. Jung, and K.-Y. Suh, "Towards the Next Level of Bioinspired Dry Adhesives: New Designs and Applications," *Advanced Functional Materials*, vol. 21, pp. 3606–3616, Sept. 2011. (document), 1.1, 1.4.3, 1.4.3, 1.5, 3.1
- [22] M. P. Murphy, C. Kute, Y. Menguc, and M. Sitti, "Waalbot II: Adhesion Recovery and Improved Performance of a Climbing Robot using Fibrillar Adhesives," *The International Journal of Robotics Research*, vol. 30, pp. 118–133, Oct. 2010. (document), 1.5.1, 1.6, 2.4.3, A
- [23] S. Kim, M. Spenko, S. Trujillo, B. Heyneman, V. Mattoli, and M. R. Cutkosky, "Whole body adhesion: hierarchical, directional and distributed control of adhesive forces for a climbing robot," in *Proceedings 2007 IEEE International Conference on Robotics and Automation*, pp. 1268–1273, IEEE, Apr. 2007. (document), 1.6
- [24] S. Kim, J. Wu, A. Carlson, S. H. Jin, A. Kovalsky, P. Glass, Z. Liu, N. Ahmed, S. L. Elgan, W. Chen, P. M. Ferreira, M. Sitti, Y. Huang, and J. A. Rogers, "Microstructured elastomeric surfaces with reversible adhesion and examples of their use in deterministic assembly by transfer printing," *Proceedings of the National Academy of Sciences of the United States of America*, vol. 107, pp. 17095–100, Oct. 2010. (document), 1.3.2, 1.7, 1.5.1, 2.1, 2.2.3, 2.4.3
- [25] Y. Menguc, S. Y. Yang, S. Kim, J. A. Rogers, and M. Sitti, "Gecko-Inspired Controllable Adhesive Structures Applied to Micromanipulation," *Advanced Functional Materials*, 2011. (document), 1.4.1, 1.7, 1.5.1
- [26] D. J. Irschick, C. C. Austin, K. Petren, R. N. Fisher, J. B. Losos, and O. Ellers, "A comparative analysis of clinging ability among pad-bearing lizards," *Biological Jounral of the Linnean Society*, vol. 59, pp. 21–35, Sept. 1996. (document), 1.2, 1.2.1, 1.3.2, A, A.5
- [27] I. Newton, Opticks. 4 ed., 1730. (document), B.1

- [28] A. Jagota and C.-Y. Hui, "Adhesion, friction, and compliance of bio-mimetic and bio-inspired structured interfaces," *Materials Science and Engineering: R: Reports*, Oct. 2011. 1.1, 1.1, 1.2.3, 3.1, 4.1.4
- [29] L. F. Boesel, C. Greiner, E. Arzt, and A. del Campo, "Gecko-inspired surfaces: a path to strong and reversible dry adhesives," *Advanced Materials*, vol. 22, pp. 2125– 37, May 2010. 1.1, 3.1
- [30] D. Sameoto and C. Menon, "Recent advances in the fabrication and adhesion testing of biomimetic dry adhesives," *Smart Materials and Structures*, vol. 19, p. 103001, Oct. 2010. 1.1, 4.1.4
- [31] M. Kamperman, E. Kroner, A. del Campo, R. M. McMeeking, and E. Arzt, "Functional Adhesive Surfaces with "Gecko" Effect: The Concept of Contact Splitting," *Advanced Engineering Materials*, vol. 12, pp. 335–348, May 2010. 1.1
- [32] A. Majumder, A. Sharma, and A. Ghatak, "Bio-Inspired Adhesion and Adhesives: Controlling Adhesion by Micronano Structuring of Soft Surfaces in Microfluids and Microfabrication," in *Microfluidics and Microfabrication* (S. Chakraborty, ed.), ch. 7, pp. 283–307, Springer, 2010. 1.1
- [33] K. Autumn, "How Gecko Toes Stick," *American Scientist*, vol. 94, no. 2, p. 124, 2006. 1.1, 1.2.3, 3.1
- [34] Aristotle, "Book IX," in *Historia Animalium*, Oxford: Clarendon, 1918. 1.2, 3.1
- [35] O. Cartier, "Studien uber den feineren bau der epidermis bei den geckotiden.," Verhandlungen der Wurzburger Phys.-med. Gesellschaft, vol. 1, pp. 239–258, 1872. 1.2
- [36] U. Hiller, "Untersuchungen zum Feinbau und zur Funktion der Haftborsten von Reptilien," Zeitschrift fur Morphologie der Tiere, vol. 62, no. 4, pp. 307–362, 1968. 1.2
- [37] K. Autumn, Y. A. Liang, S. T. Hsieh, W. Zesch, W. P. Chan, T. W. Kenny, R. Fearing, and R. J. Full, "Adhesive force of a single gecko foot-hair," *Nature*, vol. 405, pp. 681–5, June 2000. 1.2, 1.2.1, 1.3.1, 1.4.1, 2.1, 3.1, A.1
- [38] K. Autumn and A. M. Peattie, "Mechanisms of adhesion in geckos.," *Integrative and Comparative Biology*, vol. 42, pp. 1081–90, Dec. 2002. 1.2, 1.2.1, 1.2.3, 1.3.1, 1.4.1, 2.1
- [39] K. Autumn, S. Hsieh, D. Dudek, J. Chen, C. Chitaphan, and R. Full, "Dynamics of geckos running vertically," *Journal of Experimental Biology*, vol. 209, no. 2, pp. 260–272, 2006. 1.2, 1.2.3, 2.1, A.1

- [40] N. E. Stork, "Experimental Analysis of Adhesion of Chrysolina Polita (Chrysomelidae: Coleoptera) on a Variety of Surfaces," *Journal of Experimental Biology*, vol. 88, pp. 91–108, 1980. 1.2.1
- [41] G. Huber, H. Mantz, R. Spolenak, K. Mecke, K. Jacobs, S. N. Gorb, and E. Arzt, "Evidence for capillarity contributions to gecko adhesion from single spatula nanomechanical measurements.," *Proceedings of the National Academy of Sciences* of the United States of America, vol. 102, pp. 16293–6, Nov. 2005. 1.2.1, 1.3.2
- [42] G. Huber, S. N. Gorb, R. Spolenak, and E. Arzt, "Resolving the nanoscale adhesion of individual gecko spatulae by atomic force microscopy.," *Biology letters*, vol. 1, pp. 2–4, Mar. 2005. 1.2.1
- [43] W. Sun, P. Neuzil, T. S. Kustandi, S. Oh, and V. D. Samper, "The nature of the gecko lizard adhesive force.," *Biophysical journal*, vol. 89, no. 2, pp. L14–7, 2005. 1.2.1
- [44] P. H. Niewiarowski, S. Lopez, L. Ge, E. Hagan, and A. Dhinojwala, "Sticky gecko feet: the role of temperature and humidity.," *PloS ONE*, vol. 3, p. e2192, Jan. 2008. 1.2.1
- [45] J. B. Puthoff, M. S. Prowse, M. Wilkinson, and K. Autumn, "Changes in materials properties explain the effects of humidity on gecko adhesion," *Journal of Experimental Biology*, vol. 213, pp. 3699–704, 2010. 1.2.1
- [46] M. S. Prowse, M. Wilkinson, J. B. Puthoff, G. Mayer, and K. Autumn, "Effects of humidity on the mechanical properties of gecko setae.," *Acta Biomaterialia*, vol. 7, pp. 733–8, Feb. 2011. 1.2.1
- [47] P. Y. Hsu, L. Ge, X. Li, A. Y. Stark, C. Wesdemiotis, P. H. Niewiarowski, and A. Dhinojwala, "Direct evidence of phospholipids in gecko footprints and spatulasubstrate contact interface detected using surface-sensitive spectroscopy.," *Journal* of the Royal Society, Interface, Aug. 2011. 1.2.1
- [48] O. Breidbach, "Die Tarsen von Insekten: ein Schoenes Beispiel von Konvergenz," *Mikrokosmos*, vol. 69, pp. 200–201, 1980. 1.2.2
- [49] E. E. Williams and J. A. Peterson, "Convergent and alternative designs in the digital adhesive pads of scincid lizards.," *Science*, vol. 215, pp. 1509–11, Mar. 1982. 1.2.2
- [50] H. Schliemann, "Haftorgane Beispiele f
  ür gleichsinnige Anpassungen in der Evolution der Tiere," *Funkt. Biol. Med*, vol. 2, pp. 169–177, 1983. 1.2.2
- [51] T. Eisner and D. J. Aneshansley, "Defense by foot adhesion in a beetle (Hemisphaerota cyanea)," *Proceedings of the National Academy of Sciences*, vol. 97, pp. 6568–6573, June 2000. 1.2.2, 2.1

- [52] O. Betz, "Performance and adaptive value of tarsal morphology in rove beetles of the genus Stenus (Coleoptera, Staphylinidae)," *Journal of Experimental Biology*, vol. 205, pp. 1097–1113, 2002. 1.2.2
- [53] S. Niederegger, "Tarsal movements in flies during leg attachment and detachment on a smooth substrate," *Journal of Insect Physiology*, vol. 49, pp. 611–620, June 2003. 1.2.2
- [54] J. D. Gillett and V. B. Wigglesworth, "The Climbing Organ of an Insect, Rhodnius prolixus (Hemiptera; Reduviidae)," *Proceedings of the Royal Society B: Biological Sciences*, vol. 111, pp. 364–376, Sept. 1932. 1.2.2
- [55] W. Federle, W. Baumgartner, and B. Hölldobler, "Biomechanics of ant adhesive pads: frictional forces are rate- and temperature-dependent," *Journal of Experimental Biology*, vol. 207, pp. 67–74, 2004. 1.2.2
- [56] R. G. Beutel and S. N. Gorb, "Ultrastructure of attachment specializations of hexapods (Arthropoda): evolutionary patterns inferred from a revised ordinal phylogeny," *Journal of Zoological Systematics and Evolutionary Research*, vol. 39, pp. 177–207, Dec. 2001. 1.2.2
- [57] W. J. P. Barnes, "Functional Morphology and Design Constraints of Smooth Adhesive Pads," *MRS Bulletin*, vol. 32, pp. 479–485, Jan. 2007. 1.2.2
- [58] M. Scherge and S. N. Gorb, Biological Micro- and Nanotribology: Natures Solutions. Berlin: Springer, 2001. 1.2.3
- [59] H. Gao, X. Wang, H. Yao, S. Gorb, and E. Arzt, "Mechanics of hierarchical adhesion structures of geckos," *Mechanics of Materials*, vol. 37, pp. 275–285, Mar. 2005. 1.2.3, 1.3.1
- [60] R. H. C. Bonser, "The Young's modulus of feather keratin," *Journal of Experimental Biology*, vol. 198, pp. 1029–1033, 1995. 1.2.3
- [61] R. H. C. Bonser, "The Young's modulus of ostrich claw keratin," *Journal of Materials Science Letters*, vol. 19, no. 12, pp. 1039–1040, 2000. 1.2.3
- [62] B. N. J. Persson, "On the mechanism of adhesion in biological systems," *Journal of Chemical Physics*, vol. 118, pp. 7614–7621, 2003. 1.2.3, 1.3.2
- [63] C. A. Dahlquist, *Treatise on Adhesion and Adhesives*, vol. 2. New York City: Dekker, 1969. 1.2.3
- [64] H. Hertz, *Miscellaneous papers*. London: Macmillan, 1896. 1.3.1

- [65] K. L. Johnson, K. Kendall, and A. D. Roberts, "Surface Energy and the Contact of Elastic Solids," *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 324, pp. 301–313, Sept. 1971. 1.3.1, 2.4.1, 2.4.2, 2.4.2, 2.4.2, 4.1.2
- [66] T. Tang, C.-Y. Hui, and N. J. Glassmaker, "Can a fibrillar interface be stronger and tougher than a non-fibrillar one?," *Journal of the Royal Society, Interface*, vol. 2, pp. 505–16, Dec. 2005. 1.3.1, 1.3.2, 1.3.2
- [67] A. Peressadko and S. Gorb, "When less is more: experimental evidence for tenacity enhancement by division of contact area," *The Journal of Adhesion*, vol. 80, pp. 247– 261, Apr. 2004. 1.3.1
- [68] C.-Y. Hui, N. J. Glassmaker, T. Tang, and A. Jagota, "Design of biomimetic fibrillar interfaces: 2. Mechanics of enhanced adhesion.," *Journal of the Royal Society, Interface*, vol. 1, no. 1, pp. 35–48, 2004. 1.3.1, 1.3.2, 1.3.2
- [69] N. J. Glassmaker, A. Jagota, and C.-Y. Hui, "Adhesion enhancement in a biomimetic fibrillar interface.," *Acta Biomaterialia*, vol. 1, pp. 367–75, July 2005. 1.3.1, 2.1
- [70] S. Kim and M. Sitti, "Biologically inspired polymer microfibers with spatulate tips as repeatable fibrillar adhesives," *Applied Physics Letters*, vol. 89, no. 26, p. 261911, 2006. 1.3.1, 1.3.2, 1.4.1, 1.4.1, 2.1, 2.2.1, 2.2.2, A.1
- [71] J. Y. Chung and M. K. Chaudhury, "Roles of discontinuities in bio-inspired adhesive pads.," *Journal of the Royal Society, Interface*, vol. 2, pp. 55–61, Mar. 2005. 1.3.1
- [72] A. Ghatak, L. Mahadevan, J. Y. Chung, M. K. Chaudhury, and V. Shenoy, "Peeling from a biomimetically patterned thin elastic film," *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 460, pp. 2725–2735, Sept. 2004. 1.3.1
- [73] E. P. Chan, C. Greiner, E. Arzt, and A. J. Crosby, "Designing Model Systems for Enhanced Adhesion," *Materials Research Society Bulletin*, vol. 32, pp. 496–543, 2007. 1.3.1
- [74] M. Varenberg, B. Murarash, Y. Kligerman, and S. N. Gorb, "Geometry-controlled adhesion: revisiting the contact splitting hypothesis," *Applied Physics A*, vol. 103, pp. 933–938, May 2011. 1.3.1
- [75] H. Gao and H. Yao, "Shape insensitive optimal adhesion of nanoscale fibrillar structures.," *Proceedings of the National Academy of Sciences of the United States of America*, vol. 101, pp. 7851–6, May 2004. 1.3.2, 1.3.2, 1.4.1

- [76] A. del Campo, C. Greiner, and E. Arzt, "Contact shape controls adhesion of bioinspired fibrillar surfaces," *Langmuir*, vol. 23, pp. 10235–43, Sept. 2007. 1.3.2, 1.4.1, 2.2.1, A.1
- [77] M. P. Murphy, B. Aksak, and M. Sitti, "Adhesion and anisotropic friction enhancements of angled heterogeneous micro-fiber arrays with spherical and spatula tips," *Journal of Adhesion Science and Technology*, vol. 21, pp. 1281–1296, Oct. 2007. 1.3.2, 1.3.3, 1.4.1, 1.4.1, 1.4.1, 2.2.1, 2.2.2, 3.2, A.1
- [78] S. Kim, E. Cheung, and M. Sitti, "Wet self-cleaning of biologically inspired elastomer mushroom shaped microfibrillar adhesives," *Langmuir*, vol. 25, no. 13, pp. 7196–9, 2009. 1.3.2, 1.4.1, 3.1, 4.1.4
- [79] A. V. Spuskanyuk, R. M. McMeeking, V. S. Deshpande, and E. Arzt, "The effect of shape on the adhesion of fibrillar surfaces," *Acta biomaterialia*, vol. 4, pp. 1669–76, Nov. 2008. 1.3.2, 1.4.1, 2.2.1
- [80] G. Carbone, E. Pierro, and S. N. Gorb, "Origin of the superior adhesive performance of mushroom-shaped microstructured surfaces," *Soft Matter*, vol. 7, no. 12, 2011. 1.3.2, 3.1, 3.3
- [81] N. J. Glassmaker, A. Jagota, C.-Y. Hui, W. L. Noderer, and M. K. Chaudhury, "Biologically inspired crack trapping for enhanced adhesion.," *Proceedings of the National Academy of Sciences of the United States of America*, vol. 104, pp. 10786–91, June 2007. 1.3.2
- [82] W. L. Noderer, L. Shen, S. Vajpayee, N. J. Glassmaker, A. Jagota, and C.-Y. Hui, "Enhanced adhesion and compliance of film-terminated fibrillar surfaces," *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 463, pp. 2631–2654, 2007. 1.3.2
- [83] L. Shen, N. J. Glassmaker, A. Jagota, and C.-Y. Hui, "Strongly enhanced static friction using a film-terminated fibrillar interface," *Soft Matter*, vol. 4, no. 3, p. 618, 2008. 1.3.2
- [84] H. Yao, G. D. Rocca, P. R. Guduru, and H. Gao, "Adhesion and sliding response of a biologically inspired fibrillar surface: experimental observations.," *Journal of the Royal Society, Interface*, vol. 5, pp. 723–33, July 2008. 1.3.2
- [85] S. Vajpayee, A. Jagota, and C.-Y. Hui, "Adhesion of a Fibrillar Interface on Wet and Rough Surfaces," *The Journal of Adhesion*, vol. 86, pp. 39–61, Jan. 2010. 1.3.2, 1.3.2, 1.3.2

- [86] N. J. Glassmaker, T. Himeno, C.-Y. Hui, and J. Kim, "Design of biomimetic fibrillar interfaces: 1. Making contact.," *Journal of the Royal Society, Interface*, vol. 1, pp. 23–33, Nov. 2004. 1.3.2, 1.4.1
- [87] A. Jagota and S. J. Bennison, "Mechanics of adhesion through a fibrillar microstructure.," *Integrative and Comparative Bology*, vol. 42, pp. 1140–5, Dec. 2002. 1.3.2
- [88] B. Bhushan, A. G. Peressadko, and T.-W. Kim, "Adhesion analysis of two-level hierarchical morphology in natural attachment systems for 'smart adhesion'," *Journal of Adhesion Science and Technology*, vol. 20, pp. 1475–1491, Oct. 2006. 1.3.2, 1.3.2, A.1
- [89] C. Hui, A. Jagota, Y. Lin, and E. Kramer, "Constraints on Microcontact Printing Imposed by Stamp Deformation," *Langmuir*, vol. 18, pp. 1394–1407, Feb. 2002. 1.3.2
- [90] K. G. Sharp, G. S. Blackman, N. J. Glassmaker, A. Jagota, and C.-Y. Hui, "Effect of stamp deformation on the quality of microcontact printing: theory and experiment.," *Langmuir*, vol. 20, pp. 6430–8, July 2004. 1.3.2
- [91] B. N. J. Persson and S. Gorb, "The effect of surface roughness on the adhesion of elastic plates with application to biological systems," *The Journal of Chemical Physics*, vol. 119, no. 21, p. 11437, 2003. 1.3.2
- [92] M. Schargott, V. L. Popov, and S. Gorb, "Spring model of biological attachment pads," *Journal of Theoretical Biology*, vol. 243, pp. 48–53, Nov. 2006. 1.3.2
- [93] C.-Y. Hui, N. J. Glassmaker, and A. Jagota, "How Compliance Compensates for Surface Roughness in Fibrillar Adhesion," *The Journal of Adhesion*, vol. 81, pp. 699– 721, July 2005. 1.3.2
- [94] P.-C. Lin, S. Vajpayee, A. Jagota, C.-Y. Hui, and S. Yang, "Mechanically tunable dry adhesive from wrinkled elastomers," *Soft Matter*, vol. 4, no. 9, p. 1830, 2008. 1.3.2
- [95] N. Cañas, M. Kamperman, B. Völker, E. Kroner, R. M. McMeeking, and E. Arzt, "Effect of nano- and micro-roughness on adhesion of bioinspired micropatterned surfaces," *Acta Biomaterialia*, Sept. 2011. 1.3.2
- [96] C.-Y. Hui, A. Jagota, L. Shen, A. Rajan, N. Glassmaker, and T. Tang, "Design of bio-inspired fibrillar interfaces for contact and adhesion theory and experiments," *Journal of Adhesion Science and Technology*, vol. 21, pp. 1259–1280, Oct. 2007. 1.3.2, 3.3

- [97] P. K. Porwal and C. Y. Hui, "Strength statistics of adhesive contact between a fibrillar structure and a rough substrate.," *Journal of the Royal Society, Interface*, vol. 5, pp. 441–8, Apr. 2008. 1.3.2
- [98] R. M. McMeeking, E. Arzt, and A. G. Evans, "Defect Dependent Adhesion of Fibrillar Surfaces," *The Journal of Adhesion*, vol. 84, pp. 675–681, Aug. 2008. 1.3.2
- [99] H. Lee, B. P. Lee, and P. B. Messersmith, "A reversible wet/dry adhesive inspired by mussels and geckos.," *Nature*, vol. 448, no. 7151, pp. 338–41, 2007. 1.3.2, 1.4.1
- [100] P. Glass, H. Chung, N. R. Washburn, and M. Sitti, "Enhanced reversible adhesion of dopamine methacrylamide-coated elastomer microfibrillar structures under wet conditions.," *Langmuir*, vol. 25, no. 12, pp. 6607–12, 2009. 1.3.2, 1.4.1, 1.4.1, 2.1
- [101] P. Glass, H. Chung, N. R. Washburn, and M. Sitti, "Enhanced wet adhesion and shear of elastomeric micro-fiber arrays with mushroom tip geometry and a photopolymerized p(DMA-co-MEA) tip coating," *Langmuir*, vol. 26, pp. 17357–62, Nov. 2010. 1.3.2, 1.4.1, 1.4.1, 2.1
- [102] E. Cheung and M. Sitti, "Enhancing Adhesion of Biologically Inspired Polymer Microfibers with a Viscous Oil Coating," *The Journal of Adhesion*, vol. 87, pp. 547– 557, June 2011. 1.3.2, 1.4.1
- [103] R. Long, C.-Y. Hui, S. Kim, and M. Sitti, "Modeling the soft backing layer thickness effect on adhesion of elastic microfiber arrays," *Journal of Applied Physics*, vol. 104, no. 4, p. 044301, 2008. 1.3.2, 2.2.2
- [104] S. Kim, M. Sitti, C.-Y. Hui, R. Long, and A. Jagota, "Effect of backing layer thickness on adhesion of single-level elastomer fiber arrays," *Applied Physics Letters*, vol. 91, no. 16, p. 161905, 2007. 1.3.2
- [105] B. Aksak, C.-Y. Hui, and M. Sitti, "The effect of aspect ratio on adhesion and stiffness for soft elastic fibres," *Journal of the Royal Society, Interface*, vol. 8, pp. 1166– 75, Aug. 2011. 1.3.2, 3.3
- [106] C. Greiner, A. del Campo, and E. Arzt, "Adhesion of bioinspired micropatterned surfaces: effects of pillar radius, aspect ratio, and preload.," *Langmuir*, vol. 23, pp. 3495–502, Mar. 2007. 1.3.2, 1.4.1, 2.1
- [107] K. Shull, "Contact mechanics and the adhesion of soft solids," *Materials Science* and Engineering: R: Reports, vol. 36, pp. 1–45, Jan. 2002. 1.3.2, 2.3.4, 2.4.1, 4

- [108] M. A. Meitl, Z.-T. Zhu, V. Kumar, K. J. Lee, X. Feng, Y. Y. Huang, I. Adesida, J. A. Rogers, and R. G. Nuzzo, "Transfer printing by kinetic control of adhesion to an elastomeric stamp," *Nature Materials*, vol. 5, no. 1, pp. 33–38, 2005. 1.3.2, 2.1, 2.4.3, 4
- [109] S. Vajpayee, R. Long, L. Shen, A. Jagota, and C.-Y. Hui, "Effect of rate on adhesion and static friction of a film-terminated fibrillar interface.," *Langmuir*, vol. 25, pp. 2765–71, Mar. 2009. 1.3.2, 4
- [110] G. Castellanos, E. Arzt, and M. Kamperman, "Effect of viscoelasticity on adhesion of bioinspired micropatterned epoxy surfaces.," *Langmuir*, vol. 27, pp. 7752–9, June 2011. 1.3.2, 4
- [111] A. Mahdavi, L. Ferreira, C. Sundback, J. W. Nichol, E. P. Chan, D. J. D. Carter, C. J. Bettinger, S. Patanavanich, L. Chignozha, E. Ben-Joseph, A. Galakatos, H. Pryor, I. Pomerantseva, P. T. Masiakos, W. Faquin, A. Zumbuehl, S. Hong, J. Borenstein, J. Vacanti, R. Langer, and J. M. Karp, "A biodegradable and biocompatible gecko-inspired tissue adhesive," *Proceedings of the National Academy of Sciences of the United States of America*, vol. 105, pp. 2307–12, Feb. 2008. 1.3.2, 1.5.2, 4
- [112] E. Cheung and M. Sitti, "Adhesion of biologically inspired polymer microfibers on soft surfaces," *Langmuir*, vol. 25, pp. 6613–6, June 2009. 1.3.2
- [113] J. M. Karp and R. Langer, "Materials science: Dry solution to a sticky problem," *Nature*, vol. 477, pp. 42–3, Sept. 2011. 1.3.2, 1.5.2, 3.1
- [114] G. Amontons, "De la résistance causée dans les machines," Mémoires de l'Académie Royale A, pp. 257–282, 1699. 1.3.3
- [115] B. N. J. Persson, Sliding Friction: Physical Principles and Applications. New York City: Springer-Verlag, 2000. 1.3.3
- [116] A. M. Homola, J. N. Israelachvili, P. M. McGuiggan, and M. L. Gee, "Fundamental experimental studies in tribology: The transition from interfacial friction of undamaged molecularly smooth surfaces to normal friction with wear," *Wear*, vol. 136, pp. 65–83, Feb. 1990. 1.3.3
- [117] A. Berman, C. Drummond, and J. Israelachvili, "Amontons' law at the molecular level," *Tribology Letters*, vol. 4, no. 2, pp. 95–101, 1998. 1.3.3
- [118] B. Aksak, M. P. Murphy, and M. Sitti, "Adhesion of biologically inspired vertical and angled polymer microfiber arrays.," *Langmuir*, vol. 23, pp. 3322–32, Mar. 2007. 1.3.3, 1.4.1, 1.4.1, 2.1, 2.2.1, 2.2.2, 2.3.3, 2.4.1, 2.4.2, 2.4.3, 3.2

- [119] Y. Tian, N. Pesika, H. Zeng, K. Rosenberg, B. Zhao, P. McGuiggan, K. Autumn, and J. Israelachvili, "Adhesion and friction in gecko toe attachment and detachment.," *Proceedings of the National Academy of Sciences of the United States of America*, vol. 103, pp. 19320–5, Dec. 2006. 1.3.3
- [120] M. Varenberg and S. Gorb, "Shearing of fibrillar adhesive microstructure: friction and shear-related changes in pull-off force," *Journal of The Royal Society Interface*, vol. 4, pp. 721–725, Aug. 2007. 1.3.3
- [121] A. Kumar and C.-Y. Hui, "Numerical study of shearing of a microfibre during friction testing of a microfibre array," *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 467, pp. 1372–1389, Nov. 2010. 1.3.3
- [122] N. Gravish, M. Wilkinson, S. Sponberg, A. Parness, N. Esparza, D. Soto, T. Yamaguchi, M. Broide, M. Cutkosky, C. Creton, and K. Autumn, "Rate-dependent frictional adhesion in natural and synthetic gecko setae.," *Journal of the Royal Society, Interface*, vol. 7, pp. 259–69, Feb. 2010. 1.3.3
- [123] L. Ge, S. Sethi, L. Ci, P. M. Ajayan, and A. Dhinojwala, "Carbon nanotube-based synthetic gecko tapes.," *Proceedings of the National Academy of Sciences of the United States of America*, vol. 104, pp. 10792–5, June 2007. 1.3.3, 1.4.2, 2.1, A.1
- [124] B. Schubert, J. Lee, C. Majidi, and R. S. Fearing, "Sliding-induced adhesion of stiff polymer microfibre arrays. II. Microscale behaviour.," *Journal of the Royal Society, Interface*, vol. 5, pp. 845–53, Aug. 2008. 1.3.3
- [125] L. Qu, L. Dai, M. Stone, Z. Xia, and Z. L. Wang, "Carbon nanotube arrays with strong shear binding-on and easy normal lifting-off.," *Science*, vol. 322, pp. 238–42, Oct. 2008. 1.3.3, 1.4.2, 3.1, A.1
- [126] H. Kinoshita, I. Kume, M. Tagawa, and N. Ohmae, "High friction of a vertically aligned carbon-nanotube film in microtribology," *Applied Physics Letters*, vol. 85, no. 14, p. 2780, 2004. 1.3.3
- [127] P. Dickrell, S. Sinnott, D. Hahn, N. Raravikar, L. Schadler, P. Ajayan, and W. Sawyer, "Frictional anisotropy of oriented carbon nanotube surfaces," *Tribology Letters*, vol. 18, no. 1, pp. 59–62, 2005. 1.3.3, 1.4.2
- [128] P. Dickrell, S. Pal, G. Bourne, C. Muratore, A. Voevodin, P. Ajayan, L. Schadler, and W. Sawyer, "Tunable friction behavior of oriented carbon nanotube films," *Tribology Letters*, vol. 24, pp. 85–90, Oct. 2006. 1.3.3
- [129] Y. Maeno and Y. Nakayama, "Geckolike high shear strength by carbon nanotube fiber adhesives," *Applied Physics Letters*, vol. 94, no. 1, p. 012103, 2009. 1.3.3

- [130] J. Lee and R. S. Fearing, "Contact self-cleaning of synthetic gecko adhesive from polymer microfibers.," *Langmuir*, vol. 24, pp. 10587–91, Oct. 2008. 1.3.3, 2.1, 2.2.3, 3.1, 3.3, 4, 4.1.4
- [131] A. G. Gillies and R. S. Fearing, "Shear Adhesion Strength of Thermoplastic Gecko-Inspired Synthetic Adhesive Exceeds Material Limits.," *Langmuir*, Aug. 2011. 1.3.3, 1.4.3
- [132] M. Sitti and R. Fearing, "Nanomolding based fabrication of synthetic gecko foothairs," *IEEE-NANO 2002.*, *Proceedings of*, pp. 137–140, 2002. 1.4.1
- [133] A. J. Crosby, M. Hageman, and A. Duncan, "Controlling polymer adhesion with "pancakes"," *Langmuir*, vol. 21, pp. 11738–43, Dec. 2005. 1.4.1
- [134] D. Soto, G. Hill, A. Parness, N. Esparza, M. Cutkosky, and T. Kenny, "Effect of fibril shape on adhesive properties," *Applied Physics Letters*, vol. 97, no. 5, p. 053701, 2010. 1.4.1, 1.4.1, 2.2.1
- [135] J. Davies, S. Haq, T. Hawke, and J. Sargent, "A practical approach to the development of a synthetic Gecko tape," *International Journal of Adhesion and Adhesives*, vol. 29, pp. 380–390, June 2009. 1.4.1
- [136] M. Lamblet, E. Verneuil, T. Vilmin, A. Buguin, P. Silberzan, and L. Léger, "Adhesion enhancement through micropatterning at polydimethylsiloxane-acrylic adhesive interfaces," *Langmuir*, vol. 23, pp. 6966–74, June 2007. 1.4.1
- [137] S. Kim, M. Spenko, S. Trujillo, B. Heyneman, D. Santos, and M. Cutkosky, "Smooth Vertical Surface Climbing With Directional Adhesion," *IEEE Transactions* on *Robotics*, vol. 24, pp. 65–74, Feb. 2008. 1.4.1, A.1
- [138] S. Kim, M. Sitti, T. Xie, and X. Xiao, "Reversible dry micro-fibrillar adhesives with thermally controllable adhesion," *Soft Matter*, vol. 5, no. 19, p. 3689, 2009. 1.4.1, 2.1
- [139] S. Reddy, E. Arzt, and A. del Campo, "Bioinspired Surfaces with Switchable Adhesion," Advanced Materials, vol. 19, pp. 3833–3837, Nov. 2007. 1.4.1, 1.4.1
- [140] H. E. Jeong, M. K. Kwak, and K. Y. Suh, "Stretchable, adhesion-tunable dry adhesive by surface wrinkling," *Langmuir*, vol. 26, pp. 2223–6, Feb. 2010. 1.4.1, 2.1
- [141] D. Santos, M. Spenko, A. Parness, S. Kim, and M. Cutkosky, "Directional adhesion for climbing: theoretical and practical considerations," *Journal of Adhesion Science and Technology*, vol. 21, pp. 1317–1341, Oct. 2007. 1.4.1, 1.5.1, A.1

- [142] A. Carlson, H.-J. Kim-Lee, J. Wu, P. Elvikis, H. Cheng, A. Kovalsky, S. Elgan, Q. Yu, P. M. Ferreira, Y. Huang, K. T. Turner, and J. A. Rogers, "Shear-enhanced adhesiveless transfer printing for use in deterministic materials assembly," *Applied Physics Letters*, vol. 98, no. 26, p. 264104, 2011. 1.4.1, 1.5.1, 2.1
- [143] H. Yoon, H. Woo, M. K. Choi, K. Y. Suh, and K. Char, "Face selection in one-step bending of Janus nanopillars," *Langmuir*, vol. 26, pp. 9198–201, June 2010. 1.4.1
- [144] J. Lee, R. S. Fearing, and K. Komvopoulos, "Directional adhesion of gecko-inspired angled microfiber arrays," *Applied Physics Letters*, vol. 93, no. 19, p. 191910, 2008. 1.4.1, 1.4.2, A.1
- [145] T.-i. Kim, H. E. Jeong, K. Y. Suh, and H. H. Lee, "Stooped Nanohairs: Geometry-Controllable, Unidirectional, Reversible, and Robust Gecko-like Dry Adhesive," Advanced Materials, vol. 21, pp. 2276–2281, June 2009. 1.4.1, 4.2.2
- [146] M. Sitti, B. Cusick, B. Aksak, A. Nese, H.-i. Lee, H. Dong, T. Kowalewski, and K. Matyjaszewski, "Dangling chain elastomers as repeatable fibrillar adhesives," *ACS applied materials and interfaces*, vol. 1, pp. 2277–87, Oct. 2009. 1.4.1, 2.1
- [147] M. Jin, X. Feng, L. Feng, T. Sun, J. Zhai, T. Li, and L. Jiang, "Superhydrophobic Aligned Polystyrene Nanotube Films with High Adhesive Force," *Advanced Materials*, vol. 17, pp. 1977–1981, Aug. 2005. 1.4.2
- [148] T. S. Kustandi, V. D. Samper, W. S. Ng, A. S. Chong, and H. Gao, "Fabrication of a gecko-like hierarchical fibril array using a bonded porous alumina template," *Journal of Micromechanics and Microengineering*, vol. 17, pp. N75–N81, Oct. 2007. 1.4.2, 1.4.3
- [149] A. Y. Y. Ho, L. P. Yeo, Y. C. Lam, and I. Rodríguez, "Fabrication and analysis of gecko-inspired hierarchical polymer nanosetae," ACS nano, vol. 5, pp. 1897–906, Mar. 2011. 1.4.2, 1.4.3
- [150] C. Majidi, R. Groff, and R. Fearing, "Clumping and packing of hair arrays manufactured by nanocasting," in 2004 ASME International Mechanical Engineering Congress and Exposition, vol. 62142, pp. 579–584, Citeseer, 2004. 1.4.2
- [151] B. Yurdumakan, N. R. Raravikar, P. M. Ajayan, and A. Dhinojwala, "Synthetic gecko foot-hairs from multiwalled carbon nanotubes," *Chemical communications*, pp. 3799–801, Aug. 2005. 1.4.2, A.1
- [152] S. Sethi, L. Ge, L. Ci, P. M. Ajayan, and A. Dhinojwala, "Gecko-inspired carbon nanotube-based self-cleaning adhesives.," *Nano letters*, vol. 8, pp. 822–5, Mar. 2008. 1.4.2, 3.1, A.1

- [153] B. Aksak, M. Sitti, A. Cassell, J. Li, M. Meyyappan, and P. Callen, "Friction of partially embedded vertically aligned carbon nanofibers inside elastomers," *Applied Physics Letters*, vol. 91, no. 6, p. 061906, 2007. 1.4.2, 2.1
- [154] C. Menon, M. Murphy, and M. Sitti, "Gecko Inspired Surface Climbing Robots," in *Proc. IEEE International Conference on Robotics and Biomimetics ROBIO 2004*, pp. 431–436, 2004. 1.5.1
- [155] M. P. Murphy and M. Sitti, "Waalbot: An Agile Small-Scale Wall-Climbing Robot Utilizing Dry Elastomer Adhesives," *IEEE/ASME Transactions on Mechatronics*, vol. 12, pp. 330–338, June 2007. 1.5.1, A, A.1, A.1, A.3.1, A.3.1
- [156] B. Aksak, M. Murphy, and M. Sitti, "Gecko inspired micro-fibrillar adhesives for wall climbing robots on micro/nanoscale rough surfaces," in *IEEE International Conference on Robotics and Automation*, 2008. ICRA 2008, pp. 3058–3063, 2008. 1.5.1, A, A.1
- [157] C. Kute, M. P. Murphy, Y. Menguç, and M. Sitti, "Adhesion recovery and passive peeling in a wall climbing robot using adhesives," in 2010 IEEE International Conference on Robotics and Automation, (Anchorage, Alaska, USA), pp. 2797–2802, IEEE, May 2010. 1.5.1
- [158] A. Asbeck, S. Dastoor, A. Parness, L. Fullerton, N. Esparza, D. Soto, B. Heyneman, and M. Cutkosky, "Climbing rough vertical surfaces with hierarchical directional adhesion," in 2009 IEEE International Conference on Robotics and Automation, pp. 2675–2680, IEEE, May 2009. 1.5.1, 2.4.3, A.1
- [159] M. R. Cutkosky and S. Kim, "Design and fabrication of multi-material structures for bioinspired robots," *Philosophical transactions. Series A, Mathematical, Physical, and Engineering Sciences*, vol. 367, pp. 1799–813, May 2009. 1.5.1
- [160] K. P. Schmidt and R. F. Inger, *Living Reptiles of the World*. Hanover House, 1957. 1.5.1
- [161] E. Cheung, M. Karagozler, and M. Sitti, "A new endoscopic microcapsule robot using beetle inspired microfibrillar adhesives," in *Proceedings*, 2005 IEEE/ASME International Conference on Advanced Intelligent Mechatronics., pp. 551–557, IEEE, 2005. 1.5.2
- [162] P. Glass, E. Cheung, and M. Sitti, "A legged anchoring mechanism for capsule endoscopes using micropatterned adhesives," *IEEE transactions on bio-medical engineering*, vol. 55, pp. 2759–67, Dec. 2008. 1.5.2

- [163] M. Sitti and R. S. Fearing, "Synthetic gecko foot-hair micro/nano-structures as dry adhesives," *Journal of Adhesion Science and Technology*, vol. 17, pp. 1055–1073, Aug. 2003. 2.1, 2.2.1
- [164] H. E. Jeong, S. H. Lee, P. Kim, and K. Y. Suh, "Stretched polymer nanohairs by nanodrawing," *Nano letters*, vol. 6, pp. 1508–13, July 2006. 2.1
- [165] A. D. Lees and J. Hardie, "The organs of adhesion in the aphid Megoura viciae," *Journal of Experimental Biology*, vol. 136, pp. 209–228, 1988. 2.1
- [166] S. Gorb, "The design of the fly adhesive pad: distal tenent setae are adapted to the delivery of an adhesive secretion," *Proceedings of the Royal Society B: Biological Sciences*, vol. 265, p. 747, May 1998. 2.1
- [167] W. Federle, "An Integrative Study of Insect Adhesion: Mechanics and Wet Adhesion of Pretarsal Pads in Ants," *Integrative and Comparative Biology*, vol. 42, pp. 1100– 1106, Dec. 2002. 2.1
- [168] Y. Zhao, T. Tong, L. Delzeit, A. Kashani, M. Meyyappan, and A. Majumdar, "Interfacial energy and strength of multiwalled-carbon-nanotube-based dry adhesive," *Journal of Vacuum Science & Technology B*, vol. 24, no. 1, p. 331, 2006. 2.1, A.1
- [169] Y. Xia and G. Whitesides, "Soft lithography," Annual Review of Materials Science, vol. 28, pp. 153–184, Aug. 1998. 2.2.1
- [170] J. Yu, S. Chary, S. Das, J. Tamelier, N. S. Pesika, K. L. Turner, and J. N. Israelachvili, "Gecko-Inspired Dry Adhesive for Robotic Applications," *Advanced Functional Materials*, vol. 21, pp. 3010–3018, May 2011. 2.2.3
- [171] G. Taubin, "Estimation of planar curves, surfaces, and nonplanar space curves defined by implicit equations with applications to edge and range image segmentation," *IEEE Transactions on Pattern Analysis and Machine Intelligence*, vol. 13, no. 11, pp. 1115–1138, 1991. 2.3.1
- [172] D. Maugis, *Contact, Adhesion and Rupture of Elastic Solids*. Berlin: Springer-Verlag, 1st ed., 1999. 2.4.1
- [173] J. A. Greenwood and K. L. Johnson, "The mechanics of adhesion of viscoelastic solids," *Philosophical Magazine A*, vol. 43, pp. 697–711, Mar. 1981. 2.4.1, 4
- [174] D. Maugis and M. Barquins, "Fracture mechanics and the adherence of viscoelastic bodies," *Journal of Physics D: Applied Physics*, vol. 11, pp. 1989–2023, Oct. 1978. 2.4.1

- [175] L. Howell, Compliant Mechanisms. New York City: Wiley, 1st ed., 2002. 2.4.2, 4.1.2
- [176] X. Liu, R. Fernandes, A. Jurisicova, R. F. Casper, and Y. Sun, "In situ mechanical characterization of mouse oocytes using a cell holding device.," *Lab on a Chip*, vol. 10, pp. 2154–61, Aug. 2010. 2.4.3
- [177] G. Simmermacher, "Untersuchungen uber Haftapparate an Tarsalgliedern von Insekten," Zeitschr. Wiss. Zool, vol. 40, pp. 481–556, 1884. 3.1
- [178] A. M. Peattie, C. Majidi, A. Corder, and R. J. Full, "Ancestrally high elastic modulus of gecko setal beta-keratin.," *Journal of the Royal Society, Interface / the Royal Society*, vol. 4, pp. 1071–6, Dec. 2007. 3.1
- [179] C. Hui, L. Shen, A. Jagota, and K. Autumn, "Mechanics of anti-fouling or selfcleaning in gecko setae," in *Proceedings of the 29th Annual Meeting of The Adhesion Society*, no. 6, pp. 29–31, 2006. 3.1, 4, 4.1.4
- [180] J. P. Díaz Téllez, D. Sameoto, and C. Menon, "Cleaning properties of dry adhesives," *Science China Technological Sciences*, vol. 53, pp. 2942–2946, Oct. 2010. 3.1, 4.1.4
- [181] Y.-C. Tsai, P.-J. Shih, T.-H. Lin, and W.-P. Shih, "Self-cleaning Effects of Biomimetic Dry Adhesives," in 2006 1st IEEE International Conference on Nano/Micro Engineered and Molecular Systems, no. c, pp. 1388–1391, IEEE, Jan. 2006. 3.1
- [182] R. Spolenak, S. Gorb, and E. D. O. j. Arzt, "Adhesion design maps for bio-inspired attachment systems," 2005. 3.3
- [183] H. Yoon, H. E. Jeong, T.-i. Kim, T. J. Kang, D. Tahk, K. Char, and K. Y. Suh, "Adhesion hysteresis of Janus nanopillars fabricated by nanomolding and oblique metal deposition," *Nano Today*, vol. 4, pp. 385–392, Oct. 2009. 4.2.2
- [184] A. Jusufi, D. I. Goldman, S. Revzen, and R. J. Full, "Active tails enhance arboreal acrobatics in geckos," *Proceedings of the National Academy of Sciences*, p. 711944105, 2008. A, A.1, A.1, A.3.1
- [185] Y. Guan, L. Jiang, and X. Zhang, "Mechanical design and basic analysis of a modular robot with special climbing and manipulation functions," in *Proc. IEEE International Conference on Robotics and Biomimetics ROBIO 2007*, pp. 502–507, 2007. A.1
- [186] T. Bretl, S. Rock, and J.-C. Latombe, "Motion planning for a three-limbed climbing robot in vertical natural terrain," *Int. Conf. on Robotics and Automation*, pp. 2947– 2953, 2003. A.1

- [187] S. P. Linder, E. Wei, and A. Clay, "Robotic Rock Climbing using Computer Vision and Force Feedback," in *Proc. IEEE International Conference on Robotics and Automation ICRA 2005*, pp. 4685–4690, 2005. A.1
- [188] S. Kim, A. Asbeck, M. Cutkosky, and W. Provancher, "SpinybotII: climbing hard walls with compliant microspines," in *ICAR '05. Proceedings.*, 12th International Conference on Advanced Robotics, 2005., pp. 601–606, IEEE, 2005. A.1
- [189] K. A. Daltorio, T. E. Wei, G. D. Wile, L. Southard, L. R. Palmer, S. N. Gorb, R. E. Ritzmann, and R. D. Quinn, "Mini-Whegs climbing steep surfaces with insectinspired attachment mechanisms," in 2007 IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 2556–2556, IEEE, Oct. 2007. A.1
- [190] L. P. Kalra, J. Gu, and M. Meng, "A Wall Climbing Robot for Oil Tank Inspection," in 2006 IEEE International Conference on Robotics and Biomimetics, pp. 1523– 1528, IEEE, 2006. A.1
- [191] J. Berengueres, K. Tadakuma, T. Kamoi, and R. Kratz, "Compliant Distributed Magnetic Adhesion Device for Wall Climbing," in *Proceedings 2007 IEEE International Conference on Robotics and Automation*, pp. 1256–1261, IEEE, Apr. 2007. A.1
- [192] W. Shen, J. Gu, and Y. Shen, "Proposed wall climbing robot with permanent magnetic tracks for inspecting oil tanks," *Mechatronics and Automation*, 2005 IEEE International Conference, pp. 2072–2077, July 2005. A.1
- [193] Y. Fei, X. Zhao, and J. Wan, "Motion Analysis of a Modular Inspection Robot with Magnetic Wheels," in 2006 6th World Congress on Intelligent Control and Automation, pp. 8187–8190, IEEE, 2006. A.1
- [194] J. Grieco, M. Prieto, M. Armada, and P. Gonzalez de Santos, "A six-legged climbing robot for high payloads," in *Proceedings of the 1998 IEEE International Conference* on Control Applications, vol. 1, pp. 446–450, IEEE, 1998. A.1
- [195] W. Wang, Y. Wang, K. Wang, H. Zhang, and J. Zhang, "Analysis of the kinematics of module climbing caterpillar robots," in 2008 IEEE/ASME International Conference on Advanced Intelligent Mechatronics, pp. 84–89, IEEE, July 2008. A.1
- [196] T. Zhu, R. Liu, X. D. Wang, and K. Wang, "Principle and Application of Vibrating Suction Method," in 2006 IEEE International Conference on Robotics and Biomimetics, pp. 491–495, IEEE, 2006. A.1
- [197] H. Kim, T. Kang, V. G. Loc, H. R. Choi, and K. W. Robot, "Gait Planning of Quadruped Walking and Climbing Robot for Locomotion in 3D Environment," *Proceedings of the 2005 IEEE International Conference on Robotics and Automation*, no. April, pp. 2733–2738, 2005. A.1

- [198] J. Xiao, N. Xi, R. Tummala, and R. Mukherjee, "Fuzzy Controller for Wall-Climbing Microrobots," *IEEE Transactions on Fuzzy Systems*, vol. 12, pp. 466–480, Aug. 2004. A.1
- [199] D. Longo and G. Muscato, "A modular approach for the design of the Alicia climbing robot for industrial inspection," *Industrial Robot: An International Journal*, vol. 31, no. 2, pp. 148–158, 2004. A.1
- [200] L. Wanli, Q. Xinghua, and Y. Yonggang, "Design and Motion Analysis of Wheel-Legged Climbing Robot," in 2007 Chinese Control Conference, pp. 149–153, IEEE, July 2006. A.1
- [201] S. Wu, M. Li, S. Xiao, and Y. Li, "A Wireless Distributed Wall Climbing Robotic System for Reconnaissance Purpose," in 2006 International Conference on Mechatronics and Automation, pp. 1308–1312, IEEE, June 2006. A.1
- [202] T. Yano, T. Suwa, M. Murakami, and T. Yamamoto, "Development of a semi selfcontained wall climbing robot with scanning type suction cups," in *Proceedings of the 1997 IEEE/RSJ International Conference on Intelligent Robot and Systems. Innovative Robotics for Real-World Applications. IROS* '97, vol. 2, pp. 900–905, IEEE, 1997. A.1
- [203] W. Yan, L. Shuliang, X. Dianguo, Z. Yanzheng, S. Hao, and G. Xueshan, "Development and application of wall-climbing robots," in *Proceedings 1999 IEEE International Conference on Robotics and Automation (Cat. No.99CH36288C)*, vol. 2, pp. 1207–1212, IEEE, 1999. A.1
- [204] Z.-y. Qian, Y.-z. Zhao, and Z. Fu, "Development of Wall-climbing Robots with Sliding Suction Cups," in 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 3417–3422, IEEE, Oct. 2006. A.1
- [205] T. Miyake and H. Ishihara, "Mechanisms and basic properties of window cleaning robot," in *Proceedings 2003 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM 2003)*, vol. 2, pp. 1372–1377, IEEE, 2003. A.1
- [206] P. Saboori, W. Morris, J. Xiao, and A. Sadegh, "Aerodynamic analysis of City-Climber robots," in 2007 IEEE International Conference on Robotics and Biomimetics (ROBIO), pp. 1855–1860, IEEE, Dec. 2007. A.1
- [207] J. Xiao and A. Sadegh, "City Climber: A New Generation Wall-climbing Robots," in *Climbing & Walking Robots, Towards New Applications* (H. Zhang, ed.), 2007. A.1

- [208] A. Yamamoto, T. Nakashima, and T. Higuchi, "Wall Climbing Mechanisms Using Electrostatic Attraction Generated by Flexible Electrodes," in 2007 International Symposium on Micro-NanoMechatronics and Human Science, pp. 389–394, IEEE, Nov. 2007. A.1
- [209] H. Prahlad, R. Pelrine, S. Stanford, J. Marlow, and R. Kornbluh, "Electroadhesive robotswall climbing robots enabled by a novel, robust, and electrically controllable adhesion technology," in 2008 IEEE International Conference on Robotics and Automation, pp. 3028–3033, IEEE, May 2008. A.1
- [210] D. Santos, B. Heyneman, S. Kim, N. Esparza, and M. R. Cutkosky, "Gecko-inspired climbing behaviors on vertical and overhanging surfaces," in 2008 IEEE International Conference on Robotics and Automation, pp. 1125–1131, IEEE, May 2008. A.1
- [211] D. Halaas, S. Bieniawski, P. Pigg, and J. Vian, "Control and Management of an Indoor, Health Enabled, Heterogenous Fleet," *Proceedings 2009 AIAA Infotech@Aerospace Conference*, no. April, 2009. A.3.2
- [212] E. Saad, J. Vian, G. J. Clark, and S. Bieniawski, "Vehicle Swarm Rapid Prototyping Testbed," in AIAA Infotech@Aerospace Conference and Unmanned...Unlimited Conference, 2009. A.3.2
- [213] B. Morisset, R. B. Rusu, A. Sundaresan, K. Hauser, M. Agrawal, J.-C. Latombe, and M. Beetz, "Leaving Flatland: Toward real-time 3D navigation," in 2009 IEEE International Conference on Robotics and Automation, pp. 3786–3793, IEEE, May 2009. A.3.2
- [214] T. Bretl, S. Lall, J. Latombe, and S. Rock, "Multi-step motion planning for freeclimbing robots," *Algorithmic Foundations of Robotics VI*, no. Section 4, pp. 59–74, 2005. A.3.2
- [215] E. Hecht and A. Zajac, *Optics*. Reading, Massachusetts: Addison-Wesley Publishing Company, Inc., 2 ed., 1974. B