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MODULAR TRANSPORTATION USING ROBO-TUGS WITH BIOMIMICRY OF GECKO FEET

Dinakar B. R.*, Jaishree G. Jalde, Bharath S.[1] and Manjunath B. T.[2]

[1]Bengaluru, Karnataka.
[2]Asst Prof. DSATM.

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***Corresponding Author**
Dinakar B. R.
Bengaluru, Karnataka.

ABSTRACT

Geckos are able to climb on walls even walk on ceilings but they don't glue, a chemical adhesive, or suction. If you touch a gecko toe it feels soft and smooth, and not sticky, at all. Gecko toes actually have very fine hairs (setae) packed 5,000 per mm^2 (three million per square inch) into the ridges (or lamellae) found on their underside. The Gecko Tape or Controllable adhesive is the kind of adhesive that sticks to the surface only during shear and does not stick during normal application of forces. To achieve this, we are using Moldmaking RTV Silicone adhesive and a millipore membrane. The controllable adhesives used by insects to both carry large loads and move quickly despite their small scale inspires the Robo-tug concept. These are small robots that can both move quickly and use controllable adhesion to apply interaction forces many times their body weight. The adhesives enable these autonomous robots to accomplish this feat on a variety of common surfaces without complex infrastructure. This work shows that using such an adhesive system enables small robots to provide truly human scale interaction forces, despite their size and mass. This will enable future robots to not only sense the state of the human environment in which they operate but apply large enough forces to modify it in response.

KEYWORDS: Geckos, Robo-Tugs, Moldmaking RTV.

1. INTRODUCTION

Like the noble ant or the sassy-yet-lovable

Tugboat, Robo- Tugs can pull more than their own weight. There are many examples of insects that use adhesive pads and other microscopic features to attach to surfaces; with these features, insects can apply interaction forces many times their body weight. Therefore, adhesives must engage and disengage to allow easy and fast release of adhesion, an insect or micro robot needs a controllable adhesive that can be activated for applying large interaction forces when required, and deactivated for movement with less energy. We use these insights as the basis for robo-tugs. The dry adhesives used for this work generate adhesion using van der Waals interactions. When placed on a surface, the wedges only make contact with their tips, with a very small area of contact. When the adhesives are loaded in shear, the wedges bend over to contact the surface on their sides. This deformation increases the real area of contact and gives the system more adhesive capability. When the shear force is removed, the wedges return to their original shape, disengaging the adhesive.

The controllable adhesive used for our work is completely inspired by gecko feet. After a lot of research has been proved that the intermolecular Van der Waals forces is responsible for the climb. The van der Waals intermolecular forces exist between all materials. The gecko is thus able to stick to a wide variety of surfaces irrespective of the surface material. The nano fibres provide millions of points of contact increasing the total adhesion. Fabrication of such an adhesive is quite a task and the most important performance requirements would be,

1. Quick attachment and detachment.
2. Adaption to any kind of surfaces.
3. Durability.

1.1. Controllable Adhesion: Conventional adhesive tape sticks when pressed on a surface. A new gecko-inspired synthetic adhesive (GSA) does not stick when it is pressed into a surface, but instead sticks when it slides on the surface. A similar directional adhesion effect allows real geckos to run up walls while rapidly attaching and detaching toes. The gecko-inspired adhesive uses hard plastic microfibers. The plastic is not itself sticky, but the millions of microscopic contacts work together to adhere. The number of contacts automatically increases to handle higher loads. A feature of the hard-plastic gecko-inspired adhesive is that no residue is left on surfaces as is left by conventional adhesive tapes. The dry adhesives used for this work generate adhesion using Van der Waals interactions at densely arrayed contact sites. The adhesive is composed of a series of 100 µm wedges made of silicone rubber. When placed on a surface, the wedges only make contact with their tips, with a very small area of contact. When the adhesives are loaded in shear, the wedges bend over to contact the surface on their sides. This deformation increases the real area of contact and gives the system more adhesive capability. When the shear force is removed, the wedges return to their original shape, disengaging the adhesive. We define such an adhesive as directional and controllable: the adhesion is controlled by an externally applied shear load. There have been many adhesive designs that are directional and could be possibly used for tugging robots, but because they are not controllable through shear load, would require alternative methods to turn on and off. Once engaged, the adhesive can generate an adhesive stress in both the normal and shear directions.

1.2. Biomimicry: Biomimicry is the imitation of the models, systems, and elements of nature for the purpose of solving complex human problems. Living organisms have evolved well-adapted structures and materials over geological time through natural selection. Biomimetics has given rise to new technologies inspired by biological solutions at macro and nanoscales.

Biomorphic mineralization is a technique that produces materials with morphologies and structures resembling those of natural living organisms by using bio-structures as templates for mineralization. Compared to other methods of material production, biomorphic mineralization is facile, environmentally benign and economic.

1.3. Gecko Feet and its structure

Chemical Structure: The interactions between the gecko's feet and the climbing surface are stronger than simple surface area effects. On its feet, the gecko has many microscopic hairs, or setae (singular seta), that increase the Van der Waals forces between its feet and the surface. These setae are fibrous structural proteins that protrude from the epidermis, which is made of β-keratin, the basic building block of human skin.

Physical Structure: The β-keratin bristles are approximately 5 µm in diameter. The end of each seta consists of approximately 1,000 spatulae that are shaped like an isosceles triangle. The spatulae are approximately 200 nm on one side and 10–30 nm on the other two sides.[6] The setae are aligned parallel to each other but not oriented normal to the toes. When the setae contact another surface, their load is supported by both lateral and vertical components.

The lateral load component is limited by the peeling of the spatulae, and the vertical load component is limited by shear force.

1.4. Hamaker's Surface Interaction

The following equation can be used to quantitatively characterize the Van der Waals forces, by approximating the interaction as being between two flat surfaces:

$$F = -\frac{A_H}{12\pi D^3}$$

where F is the force of interaction, AH is the Hamaker constant, and D is the distance between the two surfaces. Gecko setae are much more complicated than a flat surface, for each foot has roughly 14,000 setae that each have about 1,000 spatulas. These surface interactions help to smooth out the surface roughness of the wall, which helps improve the gecko to wall surface interaction.

2. Synthetic Setae

Synthetic setae emulate the setae found on the toes of a gecko and scientific research in this area is driven towards the development of dry adhesives. Geckos have no difficulty mastering vertical walls and are apparently capable of adhering themselves to just about any surface. The 5-toed feet of a gecko are covered with elastic hairs called setae and the ends of these hairs are split into nanoscale structures called spatulae. The sheer abundance and proximity to the surface of these spatulae make it sufficient for Van der Waals forces alone to provide the required adhesive strength.

2.1. Parameters: The key parameters in the design of synthetic gecko adhesive include:

- Pattern and periodicity of the synthetic setae.
- Hierarchical structure.
- Length, diameter, angle and stiffness of the shafts.
- Size, shape and stiffness of the spatula.
- Flexibility of the substrate.

There is a growing list of benchmark properties that can be used to evaluate the effectiveness of synthetic setae, and the adhesion coefficient, which is defined as:

$$\mu' = \frac{F_{Adhesion}}{F_{Preload}}$$

3. Fabrication of Gecko Tape

The fabrication of the Gecko Tape is a thermochemical process where the base material when mixed with the catalyst undergoes exothermic reaction and cures to form a rubbery adhesive. This process is called vulcanization and since the procedure is carried out in room temperature conditions, this is called as Room Temperature Vulcanization (RTV). For the formation of synthetic setae on the working surface of the tape, the mixture of base and the catalyst is made to cure on an isoporic Nylon-66 membrane of membrane diameter 47mm and pore diameter of 0.45µm. During the 16 hours of curing process, the mixture diffuses through the pores of the membrane at a nanoscopic level and forms tiny hair-like structures at the bottom. These are known as synthetic setae. These tiny hairs when comes in contact with the smooth surface creates a Van der Waal force between the surface and the gecko tape to provide adhesion. The special property of this adhesive is that it provides adhesion only during the application of shear forces and not during the application of normal forces. This property provides rigid footing during the puling action.

3.1. MATERIALS

Moldsil 15 Plus: Moldsil-15 PLUS is a premium grade condensation curing type Silicone RTV, recommended for mold making applications. This is a flowable grade, having high mechanical strength and cures with various catalyst options at room temperature to a flexible elastomer.

TECHNICAL OVERVIEW

UNCURED PROPERTIES

PROPERTY	STANDARD	UNITS	VALUE
Colour			White
Viscosity Component A		mPa.s	23000
Specific Gravity	ASTM D-1475		1.15
Mixed Viscosity	ASTM D-2393	mPa.s	18000
Pot-life			
With 5% CAT-24	ASTM D-2471	Min.	100
With 5% CAT-16	ASTM D-2471	Min.	30
With 5% CAT-04	ASTM D-2471	Min.	20

CURED PROPERTIES* (With 5% CAT-16)

PROPERTY	STANDARD	UNITS	VALUE
Hardness	ASTM D-2240	Shore A	15
Tensile Strength	ASTM D-412	MPa	4.5
Elongation	ASTM D- 412	%	600
Tear Strength	ASTM D-624	N/mm	18
Linear Shrinkage		(%)	<0.5

CAT-16: Medium speed Catalyst: Catalyst with moderate work life for fast demolding. Takes about 16 hours at room temperature for complete curing.

CATALYST PROPERTIES

PROPERTY	CAT-24	CAT-16	CAT-04
Colour	Transparent	Transparent	Transparent
Density (g/cc)	0.95-0.97	0.95-0.97	0.97-0.99
Viscosity (mPa.s)	25	25	25
Mix Ratio (A:B)	100:5	100:5	100:5

Nylon 66 Millipore Membrane: High-quality nylon membranes are suitable for filtering aqueous solutions and most organic solvents. The membranes are suitable for use with a wide range of biological preparations and can be used where other membranes are unsuitable. The membranes used are thin circular sheets of diameter 47mm having pores of diameter 0.45µm. The membranes are hydrophilic, eliminating the need for wetting agents that could be extracted when filtering aqueous solutions. The membranes are flexible, durable and tear resistant, and can be autoclaved at 135ºC

3.2. Procedure

Surface Preparation: The master surface is the ceramic tile and it should be clean, free of loose materials and dust particles. With porous substrates use a suitable release agent such as petroleum jelly or soap solution. Attach the double-sided tape onto the ceramic tile and carefully affix the Nylon-66 membrane on the double sided tape. Slowly rub the top surface to remove the trapped air inside of the membrane.

Mixing of Components: Thoroughly stir Moldsil-15 PLUS before addition of catalyst, as filler separation might have occurred during prolonged storage. This is an important step to get the desired performance. Select a beaker for mixing which is 4-5 times larger than the total material to be mixed. Weigh the A and B components in the desired ratio (ex: 10:1). Stir vigorously for several minutes scraping the sides and the bottom of the container to produce a homogeneous mix. Hand or mechanical (power) mixing can be used but do not mix for an extended period of time to avoid entrapping large amounts of air or causing over heating resulting in shorter work life.

De-aeration: It is recommended that entrapped air be removed under vacuum to eliminate voids in the final product. This process will make the mixture to expand and then collapse. A volume increase of about 4-5 times will occur during the de-aeration process. Therefore, a large container should be used to accommodate this volume change. It should be also noted that prolonged application of vacuum will remove the volatiles from the mixture that can result in poor cure. This system is sensitive to temperature and humidity and therefore can influence the cure speed. However, the final mechanical properties of the mold will be attained in one week. The material will cure to a flexible rubber within 24 hours at room temperature and the mold can then be separated from the master surface.

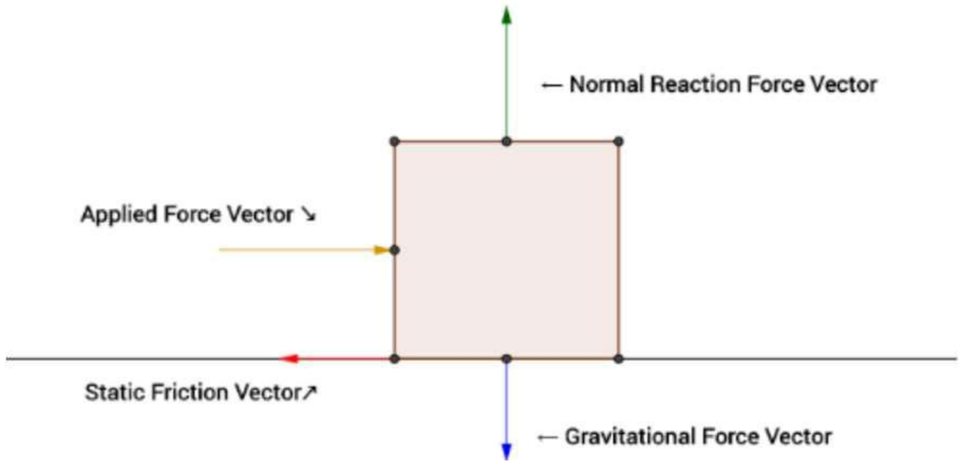
Pouring the mixture and curing: The mix should be poured as soon as possible on to the original master surface to avoid air entrapment. Pour the mixture onto the membranes attached on the ceramic tile slowly and ensure even distribution of the adhesive. The material will cure at a speed depending on the selection and the amount of the catalyst. Since the catalyst used here is CAT-16, it will take 16 hours for the mixture to cure completely. To maintain composed curing, the setup has to be kept in an environment of moderate humidity and room temperature.

Removal of Formed Gecko Tape: After the mixture has been allowed to cure for 16 hours, the gecko tape formed has to be removed carefully so as it get an even peel. The tape has to be held by a corner and has to be removed slowly with applying force at an angle more than 30 degrees from the surface. The tape has to be finally cut in the required shape. The synthetic setae will be formed on the surface that was in contact with the membrane. The gecko tape is ready to be used.

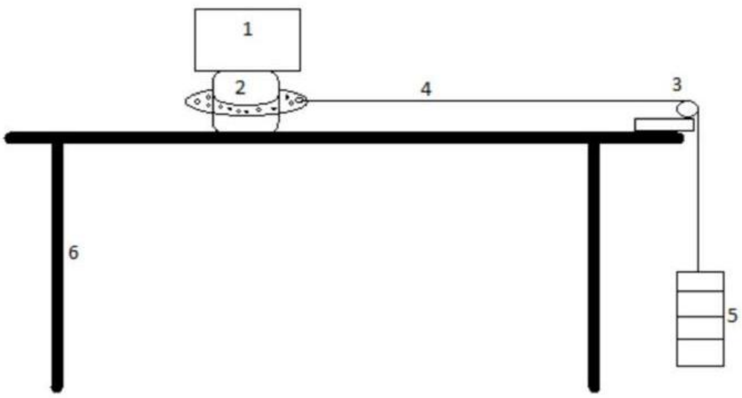
4. Testing

The testing of the gecko tape prepared was done to measure the coefficient of adhesion. The other essential parameters also include pattern and periodicity of the synthetic setae, size and shape of the spatulas and the flexibility of the substrate. However, to measure the pattern and periodicity of the synthetic setae, we require a Scanning Electron Microscope(SEM) with 10^{-7} magnification capacity. We did not find labs willing to provide us testing time on the SEM machine and hence we could not conclusively measure the pattern and periodicity of synthetic setae formed.

Test Principle: When the applied force overcomes the frictional resistance, the body yields and moves along the direction of the applied force. The Gecko Tape adheres to the surface only during shear and not during normal force. The experiment done is to determine the amount of work that is to be done to displace the gecko tape by 500µm(0.5mm). This point is known as point if slippage or point of slide. The experiment is done on surfaces of varied hardness and the coefficient of adhesion for different surfaces are carried out.



Test Setup



1. Perpendicular Preload, 2. Gecko Tape with perforated metal sheet, 3. Pulley, 4. Rope, 5. Parallel Force, 6. Work Bench.

The test setup involves a workbench which acts as the master surface for the synthetic setae. The gecko tape with perforated metal sheet fabricated as a test specimen is placed on the work table master surface. A weight is placed on the gecko tape it acts as the perpendicular preload force. The rope is passed through one of the holes in the specimen and is passed through the pulley where dead weights are applied which acts as the parallel force to the synthetic setae in contact with the work surface. The amount of load at which the gecko tape slides is calculated.

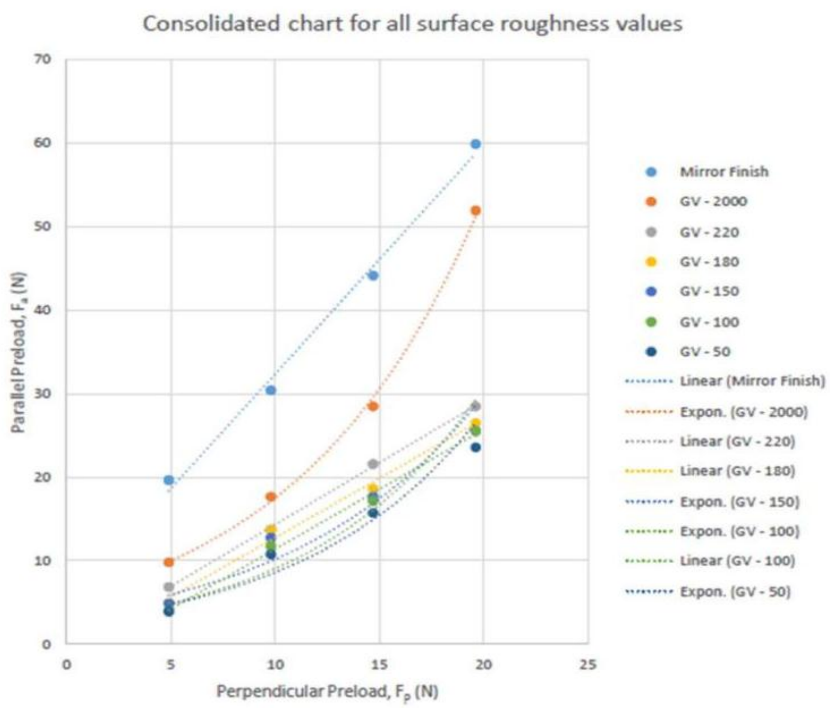
Test Procedure

- The master surface is cleaned thoroughly. The roughness factor Ra of the surface is measured.

- The gecko tape is placed on the master surface and perpendicular preload of 0.5 kg is applied on it.
- The dead weights in progression of 100g are added as a parallel force.
- The measure of weight at which the gecko tape slips by 500µm is noted down. The magnitude of this force is the point of slippage (POS) and the corresponding perpendicular force is F preload and the parallel force is F adhesion.
- The perpendicular preload is now increased to 1kg and the experiment is repeated to note down the POS. This procedure is carried out till the preload is 2kg in steps of 0.5kg.
- The graph of Fadhesion vs Fpreload is plotted. The slope of this graph is coefficient of adhesion (µ') for a given surface roughness Ra.
- The same experiment is carried out for different roughness factors of master surface.
- A graph of Ra vs µ' is plotted. The nature of graph is analysed to conclude the nature of controllable adhesion on surfaces of different roughness.

5. RESULTS

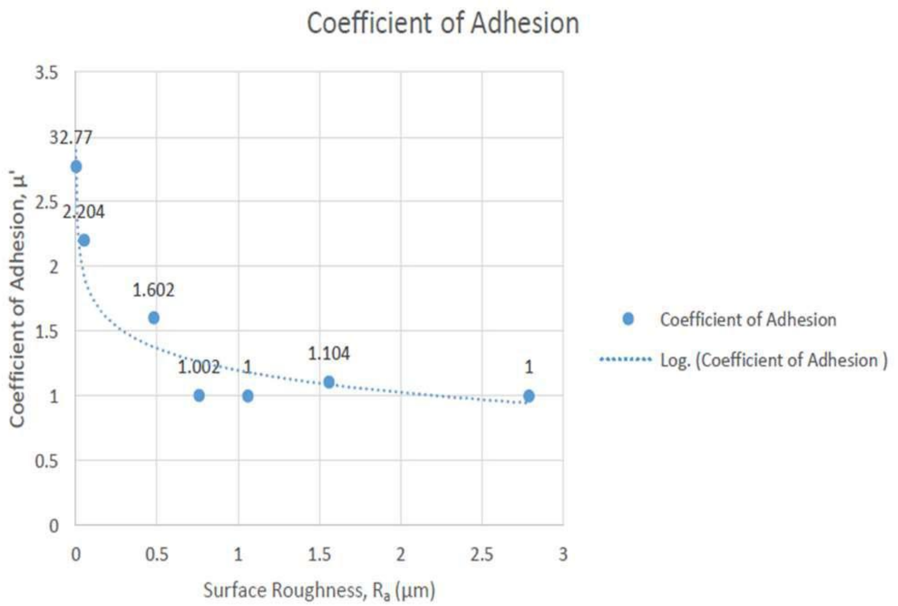
The graph indicates the Points of Slippage for different amount of Perpendicular Load. The slope is calculated to find the coefficient of adhesion. On the smoothest surface, the µ' of the lizards/geckos is approximately 8~16. We have been able to mimic almost 35% of the characteristics of the actual lizard. Let us see the progression of CoA as the roughness increases in the following graphs.



The surface roughness and the coefficient of adhesion chart is as follows:

Surface Roughness (R_a)	Coefficient of Adhesion (μ')
0.001	2.77
0.05	2.204
0.48	1.602
0.76	1.002
1.06	1
1.56	1.104
2.79	1

The corresponding graph is as follows:



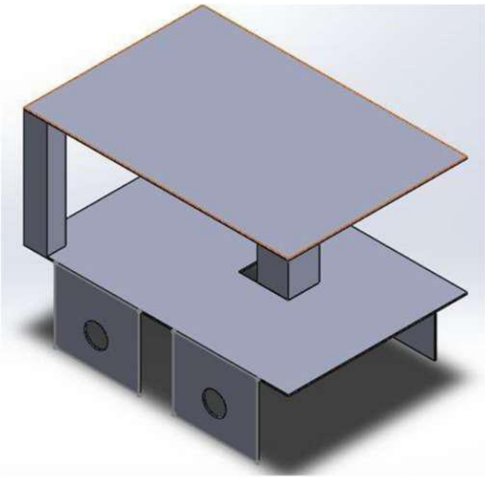
From the graph, we can clearly conclude that the property of controllable adhesion increases with decrease in the roughness of the surface i.e. controllable adhesion is inversely related to surface roughness.

6. Robo-tug

The present technologies work on the principle of friction and rigid support but in recent years due to development of controllable adhesives which provides more traction, the transportation of heavy loads can be done effectively. Incorporating these technologies, we've developed a robot that uses gecko adhesives to help in transportation of heavy components.

Parts of the Robo-tug

Chassis: A chassis consists of an internal framework that supports a manmade object. It's analogous to an animal's skeleton. An example of a chassis is the under part of a motor vehicle, consisting of the frame (on which the body is mounted) with the wheels and machinery. Material used is Mild steel (MS) because of its good welding property, economic machining process, adds on to the weight of the robot so as to increase the normal force acting on the Gecko-tape stuck to the bottom plate, cheap and easily available.



Stepper motor: A stepper motor is a brushless DC electric motor that divides a full rotation into a number of equal steps. The motor's position can then be commanded to move and hold at one of these steps without any position sensor for feedback (an open-loop controller), as long as the motor is carefully sized to the application in respect to torque and speed. The role of the stepper motor is to control the up and down movement of the base plate, to winch the load closer to the robot, to ensure the directionality of the forces.

Rack and pinion: A rack and pinion is a type of linear actuator that comprises a pair of gears which convert rotational motion into linear motion.

Pinion specifications are:

a. outer diameter, D = 22 mm;
b. Inner diameter, d = 18 mm;
c. Pitch diameter, p = 20 mm;
d. Module, m = 1.

Rack specifications are

a. Rack length, l = 75 mm;

b. Module, m = 1.

Carabiner: A carabiner or karabiner is a specialized type of shackle, a metal loop with a spring-loaded gate used to quickly and reversibly connect components, most notably in safety-critical systems.

Synthetic Setae / Gecko Tape: The heart and the principle of this project is the Gecko Tape that has synthetic setae. This tape gets attached to the ground and provides controlled adhesion i.e., the tape provides adhesion only when in shear and not during the application of normal forces. This enable the robot to gain rigid footing when the pulling action is taking place.

Winch and spool: A winch is a mechanical device that is used to wind up or wind out or otherwise adjust the tension of a rope. In its simplest form, it consists of a spool and attached hand crank. In larger forms, winches stand at the heart of machines as diverse as tow trucks, steam shovels and elevators. Spool, a usually low-flanged or un flanged cylinder on which thread, wire, cable, paper, film, straps, or tape is wound for distribution or use.

6.1. Actuation: Actuation is basically putting the process into action. In this project, the actuation is done by electronic methods.

Arduino Mega: The Arduino Mega 2560 is a microcontroller board based on the ATmega2560. It has 54 digital input/output pins (of which 14 can be used as PWM outputs), 16 analog inputs, 4 UARTs (hardware serial ports), a 16 MHz crystal oscillator, a USB connection, a power jack, an ICSP header, and a reset button. It contains everything needed to support the microcontroller; simply connect it to a computer with a USB cable or power it with a AC-to-DC adapter or battery to get started.

Programming: The Mega 2560 board can be programmed with the Arduino Software (IDE). For details, see the reference and tutorials. The ATmega2560 on the Mega 2560 comes pre-programmed with a bootloader that allows you to upload new code to it without the use of an external hardware programmer. It communicates using the original STK500 protocol (reference, C header files). The ATmega16U2 (or 8U2 in the rev1 and rev2 boards) firmware source code is available in the Arduino repository.

7. CONCLUSION

Controllable adhesives make it possible to exert very large interaction forces in comparison to body weight and friction. However, they necessarily consume a certain amount of work and require a certain amount of time to engage and disengage with each loading cycle. In general, taking fewer and longer cycles or steps to cover a given distance is desirable, although this is increasingly difficult to do at small scales. For a given robot size, these considerations favor certain types of actuators over others. For example, stepper motor actuators may have difficulty achieving a sufficiently long stroke to engage and disengage the adhesive with each cycle. SMA actuators have a force-displacement profile that is well matched to the needs of controllable directional adhesives, can be very small, and can produce robots with very high interaction forces. However, the speed and efficiency are low. If the robot is large enough to use a continuously rotating motor (electromagnetic, piezoelectric or otherwise) and gearbox, the actuation cycle can be tailored to the needs of the adhesive for impressive performance. As expected, the efficiency increases with increasing step size due to the parasitic losses in the loading and unloading of the system including the adhesives as well as all other components that deform with such large loads. As new adhesives with different engagement and disengagement characteristics are developed, these trade-offs can be revisited. The performance also depends on the ratio of maximum adhesion to the coefficient of friction between the surface and the payload the robot is pulling. Glass is a particularly good material in this regard. From the experiments carried out on the gecko adhesive fabricated, we were successful in mimicking around 35% of the controllable adhesion property of the actual live gecko feet. The further analysis carried out on the data obtained, we can conclude that the adhesion property is inversely related to the surface roughness.

8. Future Scope

Future improvements in performance will be possible if controllable directional adhesives can be optimized for a specific application, size range and set of surfaces. Given an actuator speed capability or chosen gait speed, an adhesive system should be optimized to minimize work and displacement while meeting the required speed. Since the adhesives do not require normal force to work, and in fact produce adhesion under load, there is no reason the same sort of small robot could not be designed to carry many times its body weight while climbing inclines or even vertical surfaces. In such applications, without the benefit of static friction holding the load in place between steps, some design changes will be need to maintain line tension through the stepping cycle.

This project has established that good amount of traction can be provided even on smooth surfaces whose coefficient of friction is very less. This can open up new pathways for anti-slippery materials and can be used where only controlled traction is necessary.

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