Gecko-Tech in Planetary Exploration and Base Operations

Thomas L. Billings[1], Robert D. McGown, Cheryl Lynn York, Bryce Walden[2]

Abstract

Geckos can walk straight up walls and across ceilings. Dr. Kellar Autumn and colleagues have discovered their secret: gecko feet have hundreds of thousands of hair-like "setae" with hundreds of submicroscopic pads ("spatulae") at each seta tip, which appear to cling by van der Waals forces to almost any surface. Unlike suction or traditional adhesives, this adhesion works under conditions of vacuum and particulate contamination, making it potentially ideal for use on the Moon and Mars. It is also remarkably strong (10 N per 100 mm^2 *in vivo*), yet quickly and easily released (Autumn *et al.* 2000).

Lavatube caves, on any world, can be one of the most extreme terrains in which to operate. The caves consist of raw, unweathered lava. Cave floors covered with random piles of large boulder "breakdown" make exploration difficult for humans or robots. The ability to traverse lavatube walls and ceilings would make such exploration much easier; this could be accomplished by using gecko-derived biomimetic technology. "Gecko-Tech" can greatly enhance efficiency and effectiveness of cave exploration and development. These technologies can also find many other uses outside of lavatubes.

Gecko-footed robots could climb to the lavatube roof and emplace permanent anchors for suspension of utilities, transportation, or even entire lunar bases. Tethers tipped with gecko-tech pads can extend the reach of robots and humans. Humans wearing a flexible skin-tight spacesuit with gecko-tech pads could climb over large rocks on lavatube floors, or up lava walls. Such a garment would be useful to climb the red cliffs of Mars or to perform maintenance work on slippery habitats.

Gecko-tech will increase the capabilities of emergency and rescue operations. It will enable new forms of sport and recreation.

Gecko-tech enhancements of human and robot mobility expand the range over which humans and robots can work, becoming an effective productivity multiplier.

The Remarkable Gecko

Gecko Attributes. Geckos are reptiles that have a nearly unique ability among vertebrates: they can walk straight up smooth walls, and even run across ceilings. This enables them to thrive in a wide range of environments, as reflected in the hundreds of gecko varieties living throughout the world today in deserts, jungles, and caves. Their ability to climb rapidly helps them escape predators. It also means their own prey — bugs and smaller animals — can find few places to hide that a gecko cannot reach.

Dr. Kellar Autumn and others (2000) have been researching the secrets of gecko adhesion and release. The mysterious gecko adhesive does not depend on suction,

[1] To whom correspondence should be sent, email itsd1@teleport.com.
[2] All authors: Lunar Base Research Team, The Oregon L5 Society, Inc., P.O. Box 86, Oregon City, OR 97045; website: http://www.OregonL5.org; email lbrt@OregonL5.org

friction, electrostatics, or secretions; nor is it affected by dirt, roughness, or moisture. Robots and human support gear using biomimetic technology based on the mechanisms of gecko mobility — “Gecko-Tech” — would leave few nooks and crannies of planetary environments inaccessible.

Gecko Feet. Geckos achieve their highly effective mobility using four feet specifically evolved to stick quickly to a surface, yet release that grip in milliseconds, for example while running. Each foot obtains 10 Newtons of adhesive force over 100 mm^2 of surface contact. The primary adhesive force is due in part to the stages of division the gripping elements undergo before they reach the actual tread surface. This adhesion is enhanced, and quick release made possible, by the overall mechanics of gecko feet. Each foot has five long, splayed, highly articulated toes, whose geometry of uncurling placement and peeling release is important to the adhesion and releasing process (Autumn *et al.* 2000).

Across the distal half of the gecko’s toe are many evenly-spaced gripping strips called “lamellae.” Each lamella is a large array of hair-like structures called “setae.” See Figure 1.

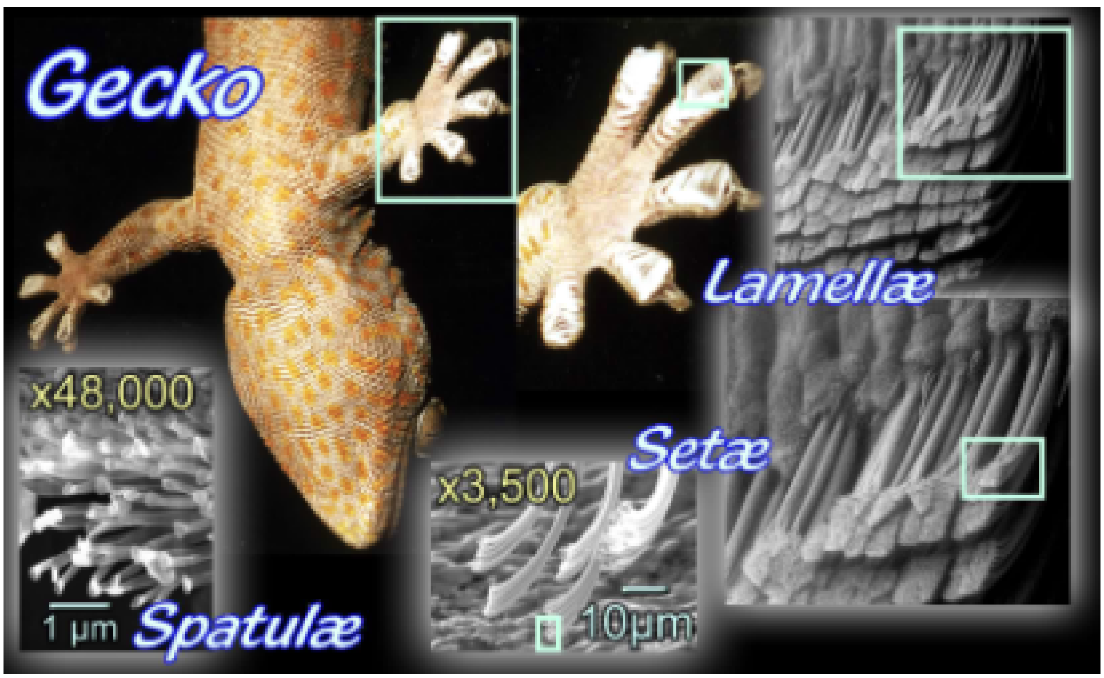

Figure 1: Secrets of Gecko Grip

(Gecko images copyright © 2000 by Kellar Autumn, used by permission)

There are about 500,000 setae on each foot. The seta is a short, delicate stalk about five microns in diameter, tipped with a brush or inflorescence of tiny pad-on-stem structures called “spatulae.”

There are between 100 and 1,000 spatulae on the end of each seta. A spatula is a short stalk with a flat disk-like pad measuring 200 to 500 nanometers in diameter. These pads are the actual gripping surface, and there are 50-500 million of them on each foot.

Autumn *et al* (2000) have measured the adhesive force of a single gecko foot-hair or seta at 194 µN. This is almost ten times stronger per unit area than the force measured *in vivo* for the gecko foot as a whole. Other researchers have eliminated suction, secretions, and electrostatic forces as the mechanism of adhesion. Autumn's experiments indicate the adhesion is most likely the intermolecular attraction known as van der Waals' force.

Gecko Locomotion. Gecko feet and toes are articulated to optimize attachment to and release from a surface. When initiating attachment, the toes uncurl "like blowing up a party favour," providing a slight (5 μm) drag at the tips of the setae. This enhances attachment forces by ten to one over simple direct placement. To detach from a surface, the toes are articulated in such a way they can peel away from the surface like tape. Detachment of an individual seta takes place when the force vector is close to 30 degrees from the surface. Extrapolating lab measurements of individual seta adhesion yields a whole-foot value of 100 $N/100mm^2$. If gecko-tech designs can approach this value, then adhesive forces normal to the surface of 1,000,000 N/m^2 may be obtainable. To put this in perspective, a 77.1 kg (170 lbs) person could be suspended in Earth gravity by a gecko-tech pad only 31.5 mm in diameter. Even reduced an order of magnitude to the level of adhesion measured *in vivo*, a gecko-tech disk 100 mm in diameter should be sufficient.

Gecko Stability. One experiment maintained adhesion under stress for 2 months, with no creep, until the experiment was terminated. This suggests gecko adhesion is long-lived with little or no decay over time. Other experiments increased strain or load beyond the adhesion holding strength, with bond failure expressed as a slippage before detachment, indicating a relatively graceful rather than catastrophic failure mode (Autumn 2001).

Artificial Gecko. Apparently, most materials with the necessary mechanical qualities of tensile strength, flexibility, and sub-micron formability, would be suitable to form artificial spatulae and setae (Autumn 2001). Nanometer-scale fabrication is not presently deemed necessary. Specific designs, materials, and methods are proprietary research at Autumn Lab. Control mechanisms for the use of gecko-tech include the ability to "set" the adhesive effect by a slight transverse tug, the ability to sense and respond to slippage or "creep" (a sign of impending failure), and the mechanical ability to apply appropriate force-geometry for release. Gecko-tech adhesion is achieved without outgassing or toxic chemicals, important in closed environments, life support, delicate or pristine environments (such as vacuum), and areas with possible ignition hazards.

Problems and Gecko-tech Solutions

Lavatube Caves. Lavatubes provide shielded volume advantageous for planetary bases and possibly preserving primordial elements (Frederick *et al.* 2000). Their arched shapes and formation as part of the bedrock make them strong and stable. However, lavatubes can be among the more difficult and hazardous terrains to negotiate. While some areas within a lavatube may have flat floors from pooled lava flows, most areas are likely to have several sorts of obstructions. Floors may have grooves, channels, bulges, drop-offs, or rough a'a surfaces from lava flow remainders (Harter III 1972). Large boulders may litter otherwise flat floors, and large piles of boulders may reach toward the lavatube roof. In addition to the uneven floor features and breakdown debris, the lava ceiling, walls, floors and boulders have edges and surfaces as sharp or convoluted as the day they formed, preserved in the lavatube shelter.

In order to use such sheltered space, exploration and inspection must be done to find usable areas and identify possible instabilities in the ceiling. Such effort is difficult for a speleologist on Earth, dressed in coveralls and breathing available air. It would be even harder for an exospeleologist wearing a clumsy spacesuit and carrying a bulky air supply. The pristine surfaces and rough breakdown are also challenging to robots. Gecko-tech would be a boon in this environment. Gecko-tech robots or “geckobots” should be able to climb over, under, and around these surfaces. Robots or humans enhanced by gecko technology could climb the walls to get around barriers and even move across the ceiling to inspect it in detail. Boulder piles may be unstable, so even when humans are using gecko-tech enhanced suits, geckobots should be sent first to scout and possibly stabilize footing. The ability of self-cleaning gecko setae to adhere in a vacuum indicates that even on the Moon, surfaces at any angle should be negotiable. This will allow penetration of lavatubes at will through any available entrance, whether straight in from a collapsed rille, or through an open skylight in the ceiling.

Once inside the lavatube, the ability to traverse walls and ceilings will allow rapid advance by avoiding floor debris altogether. Gecko-tech enhanced robots or humans can more easily haul in equipment and emplace permanent wall and ceiling anchors. Since potential adhesive forces calculated for gecko-tech pads run to 100 Newtons per 100 mm^2, or 1,000,000 N/m^2 (≈102 metric tons), these quickly- and easily-emplaced pads can be used as temporary anchors.

Other Planetary Environments. Due to the variety and difficulty of environments found in lavatubes, solutions to these problems should also be useful for similar situations encountered on planetary surfaces. An areologist (Mars geologist) could climb the walls of immense martian valleys to examine their secrets in detail. Explorers on ice worlds may be able to scale fractured ice cliffs with relative ease. On minor planets or asteroids with low gravity, people and equipment could be tethered to boulders to prevent unwanted motion, levitation, or escape.

Spacecraft and Space Stations. The ability to stick to smooth surfaces provides secure footing for personnel or robots inspecting the exteriors of spacecraft and space stations, or undertaking construction in zero-g. This technology would not require additional handholds grafted onto smooth metal surfaces. With more options for movement, EVAs can be planned more flexibly. Likewise, maintenance of inflatable habitats, or those with skins of metal or glass, should become much easier. Gecko-tech tethers can adhere to most surfaces without depending on special fixtures. They could be useful for manipulation of construction parts, or emergency holds for equipment or disabled astronauts. Docking systems for spaceships can be made more flexible through gecko-tech adhesion for initial contact.

Biomimetic Geckobots

“Geckobots” are robots designed to mimic gecko capabilities, using gecko-derived technology and designs. In addition to setae, nature uses claws, interlock members, glue, and silk extrusions for attachment: all of these should be considered in adapting gecko-tech to various environments (Autumn 2001). Geckobots may be able to perform a number of functions in lavatube caves, surface activities, planetary bases, spacecraft, and space bases or stations.

Exploration. Biomimetic geckobots used on steep regolith slopes leading into lavatube skylight entrances should have a low center of gravity and a belay line to increase security on the loose, unstable surface. At the base of the regolith slope, the geckobots will grip the vertical basalt walls of the skylight and carry their line and their sensor and construction equipment to the base of the breach. There the line can be left for pickup or later use. The geckobot can easily transition to the negative slope of the tube ceiling, carrying sensors or construction apparatus.

Mechanical footpads can sample lavatube features by either picking up rocks from surfaces, or by stabilizing drills and cutters that will carve out cores or samples for retrieval to the surface. Chemical analysis of lavatube and other surfaces may proceed wherever the geckobot finds stable footing. Gecko-tech pads with built-in micro/nanochemical sensors could analyze rock surfaces at a high level of detail. Mechanical strength tests of particular sites within the lavatube can be conducted *in situ*, by setting one foot to pulling on the rock, while the others push against the rock. Measuring the forces involved in any separation of the lava will give an example of the minimum force needed to break the lava at a particular anchor site.

Excavation. Geckobot samples or reconnaissance of materials and their average sizes will affect later choices for excavation. When large boulders are mixed with regolith in a rille entrance, the best excavation method may include large numbers of small geckobot excavators that undercut the larger boulders by removing finer regolith. Large boulders blocking the rille entrance could be blasted away using explosive charges placed by geckobots. Smaller debris can then be excavated by geckobots. Alternatively, gecko-tech pads may be used like double-sided tape to stabilize some boulders.

Construction. In skylight entrances, geckobots will be better able to place anchors on both the vertical and negative (ceiling) slopes than robots without gecko-tech, or humans hanging from a belay. Where bases are to be suspended from the ceiling, stabilizing rock bolts and suspension anchors can be emplaced by geckobots. Geckobots could emplace wall anchors for equipment, lateral stabilization, or long-term sensors faster than humans using conventional methods such as ladders, scaffolding, or belays. To prepare a rille entrance to a lavatube, geckobots can fill gaps between breakdown boulders and stabilize the ceiling to make the entrance safe for continued use. Geckobots should be able to deliver regolith gravels deep into piles of boulders to fill gaps that might otherwise allow unstable boulders to move, or that could become traps for robots, vehicles, or humans. Networked systems of geckobots working together would allow such tasks to proceed at a good pace with bucket-brigades and other transfers of material.

Larger geckobots could carry subcomponents of initial base assemblies into the cave to their intended locations even before construction of tube transport systems. Their ability to walk on walls and ceilings will permit more routes and faster transit times between the surface and the lavatube interior base site.

Gecko-Tech Equipment

Gecko-pad. The simplest piece of gecko-tech equipment would be the basic gecko-pad. With a flexible substrate, gecko-pads of various sizes can be folded or rolled for compact storage and transportation. A pad with gecko-tech on one surface could have various attachments on the other surface, such as hooks, pulleys, cable guides, etc. A double-sided gecko-tech pad would perform the functions of a vacuum- and dust-rated double-sided tape, for temporarily holding tools or containers around a workspace, mounting signs, perhaps even stabilizing boulders by sticking them together. Scientists could stick sensors virtually anywhere, from rock walls to the interiors of processing tanks. Security agents and law enforcement could quickly and easily mount cameras or other equipment where and as needed without mounting hardware or marring the underlying surface.

Gecko-tether. A “gecko-tether” is a line incorporating a gecko-tech pad at one or both ends. Traverses across walls and ceilings of planetary structures may be enhanced by use of a couple of gecko-tethers, one of which can be rapidly released behind an explorer once the other gecko-tether, thrown ahead, is securely adhering to the targeted surface. Semi-permanent gecko-tethers could suspend working equipment and building materials during construction and maintenance activities.

Gecko-tether–derived Rotary Launcher. The proposed use of rotary launchers to export materials from the lunar surface also supposes a means to grip and release such payloads (Baker and Zubrin 1990). Gecko-tech release pads might be a cheap means to hold many substances, with different surface characteristics, while ensuring a rapid and precise release from the launcher in hard vacuum. This would make launcher operations more generally capable and cost-effective. Low velocity capture of materials for the orbital end “catcher” of a rotary tether transport system would also be made more reliable using surfaces covered with artificial setae.

Gecko-tech Transport. Humans will need transportation throughout many planetary environments over longer distances and times than would be practical in a spacesuit. Gecko-tech enhancement of walking, wheeled, or tracked transports will allow maximum capability for extended transport EVAs. Because the Apollo 15 Lunar Rover was excluded from the slopes of Hadley Rille, the primary mission objective of rille characterization was not fully realized by direct observation or sampling. Applying gecko-tech to planetary exploration vehicles would allow them to investigate more places, more safely, than vehicles not so equipped.

Moving equipment around in the confines of a lavatube or on other planetary terrain requires agility that gecko-tech can deliver, especially when non-standard routes for transport would be useful. The ability to climb over obstacles will save time over a more conservative “going around” approach, if that’s even possible.

Within a base itself, operations are often constrained by the flexibility of the transport arrangements. The capabilities of gecko-tech equipped vehicles will allow use of more surfaces than flat prepared walkways and boulevards within the base. This will permit higher transport densities than where vehicles are constrained to using level or nearly level surfaces. A more compact base design would then be possible.

Gecko-suit. The addition of multiple gecko-style adhesive pads to the hands, knees, feet, and elbows of space suits can enable vertical and even inverted mobility in either lunar or martian gravity fields. Human inspection of the walls and ceilings of lavatubes above floor level is within the capability of a gecko-suited engineer. Gecko-tech’s ability to adhere to smooth surfaces means inspection and maintenance on metal, glass, or inflatable structures would be easy and safe.

Gecko-sport. Humans will want to engage in sports and recreation in any environment they inhabit. Gecko-tech will enable rock climbing, exploration and other activities to be far safer and less strenuous than at present. A gecko-tech catcher’s mitt would never drop the ball!

Gecko-rescue. In exploration, recreation or construction, accidents will undoubtedly occur. Crews wearing gecko-tech suits will be swifter, safer, and more secure in their efforts to find and rescue the unfortunate. A patient could be quickly immobilized and secured on a gecko-tech litter, which can then be maneuvered about without worrying that the patient might fall off. Gecko-tech straps could be deployed rapidly and securely and be released quickly and easily without buckles or knots.

Conclusions

Gecko-tech extends capabilities. Gecko-tech expands exploitable terrain and human, robotic, and transport capabilities.

Higher return on investment. Gecko-tech opens more possibilities for each dollar spent on a planetary base. It allows greater efficiency in allocating resources and creates more ways to gain financial return on investments.

Better safety margins. Expanding the options for physical mobility and stability improves safety in exploration, construction and operation of planetary bases.

More productivity for planetary development. The combination of better potential for financial returns, and more secure investment through better safety for each base site, allows more productivity for investments to expand human activities throughout the solar system.

Gecko-tech is an enabling technology that multiplies the effectiveness of humans, robots, and equipment. Development of gecko-tech adhesion technology on Earth in coming years will make it a natural addition to the toolkit of planetary pioneers.

Bibliography

Autumn, K. (2001). Personal communication.

Autumn, K., *et al.* (2000). "Adhesive force of a single gecko foot-hair." *Nature*, 405, pp. 681-685.

Baker, D., and Zubrin, R. (1990). "Lunar and Mars Mission Architecture Utilizing Tether-launched LLOX." *26th Joint Propulsion Conference*.

Frederick, R. D. G., Billings, T. L., McGown, R. D., and Walden, B. (2000). "Martian Ice Caves" *Concepts and Approaches for Mars Exploration*, Houston TX, p. 114–117.

Harter III, J. W. (1972). "Morphological Classification of Lava Tubes." *Proceedings of the International Symposium on Vulcanospeleology and its Extraterrestrial Applications*, Halliday, W. R., ed., Western Speleological Survey with National Speleological Society, Seattle, WA, pp. 74-85.