A Spoke-Wheel Based Wall-climbing Robot

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Abstract— **Biomimetics and biorobotics form a thriving field of modern scientific research endeavors. The development of wall-climbing robots boasts a wide array of potential real-world applications. With this technology still in progression, a simple and fundamentally sound robot has been created to serve as a test bed and proof-of-concept robot. The developed robot is inspired by the concept of Mini-WhegsTM robot. It features more robust compliant adhesive feet, a preloading tail and modular design with inexpensive educational parts. Experiments have demonstrated the capabilities of this robot such as traversing horizontal, oblique, and vertical smooth surfaces, "walking" upside down and making the transition between orthogonal surfaces.**

Keywords— Biomimetics, wall-climbing robot

I. INTRODUCTION

Even the smallest innovations can lead to significant technological developments. As the term biomimetics quickly spreads through scientific and engineering vernacular, progress is achieved daily in countless research endeavors. Combining biological influence with engineering know-how and implementation currently leads to a new wave of laboratory-created materials, machines, and robots that could potentially alter several realms of our existence.

Within the study of biomimetics lie various scopes of biorobotic investigation and advancement. Hexapedal, aquatic, amphibious, snake-like, water-striding, flying, and wall-walking robots all use nature's inspiration as the foundation for robotic design. Wall-climbing robots are particularly remarkable, given their unique ability to scale surfaces in a manner largely in-dependent from the forceful effects of gravity. Such robots have a variety of potential application on Earth as well as in space: search and rescue activities, scaling uneven terrains of rubble after a disaster in an effort to find life; access humanly inaccessible areas like sky-scrapers, bridges, or highway underpasses for inspection, repair, or personal assistance; military uses such as surveillance, reconnaissance, and mine/bomb diffusion; unusual atmospheric and environmental conditions like vacuums, under water, in volcanoes, or in space exploration, excavation, and construction; entertainment by way of toys, sporting equipment, and/or new sporting games. Regardless of their prospective uses, climbing robots are undoubtedly significant and worthy of development.

Wall-climbing robots come in many shapes and forms, but all function with the general purpose of walking along surfaces regardless of gravity and surface orientation. Suction robots like Hyperion, MRWALLSPECT, and the Micro Wall Climbing Robot use various components to generate vacuum or suction power in foot-like suction cups [1] [2] [3]. Often used as window washers, these robots have limited functionality. They require smooth, clean, featureless surfaces and move very slowly. The components needed to generate enough suction to keep the robot on a vertical surface are unavoidably heavy and greatly limit range and mobility. Also, loss of suction at one cup could potentially cause the whole machine to topple.

Some wall-climbing robots use magnets to stay attached to a surface [4]. For obvious reasons, magnetic robots only work on ferrous surfaces. They are usually extremely heavy and bulky, which subsequently make them slow and impractical. Other robots like the LEMUR IIb grasp "holds" in continuous free-climbing motion [5]. Without adequate holds in reachable locations, these robots may be left stranded.

Furthermore, pressure sensitive adhesive robots are being developed, relying on chemistry as opposed to geometry. Robots like the Mecho-Gecko and the Geckobot require smooth surfaces so that the adhesive may stick [6] [7]. The same goes for robots like Mini-Whegs™, and the Leg and Tread Based Locomotion Mechanisms, which use adhesive pads/treads that rotate continuously via motors [8] [9][15]. In contrast, spine-climbing robots like the Spinybot and the RiSE platform require porous surfaces like brick, stucco, or concrete in order for the spines to grasp [10] [11].

Despite the fact that each one of the aforementioned wall-climbing robots, including the one described in this paper, is not perfect, all of them may be considered innovative and technologically significant. They demonstrate that we are only a few advancements away from a generation of robot that can walk vertically on any surface. With that said, it must be noted that each of these robots share common biological inspiration—the gecko. The developers of each of the wall-climbing robots consider their robots to be preliminary prototypes—early phases of an ultimate robot that closely mimics the extraordinary behavior of a gecko.

Motivated by the concept of Mini-WhegsTM [8], we have developed a similar kind of wall-climbing robot that uses compliant adhesive feet. It has been named "geckGO". GeckGO is introduced with improved compliant feet, new features for robustness and modular designs. Fig. 1 shows the prototype of geckGO. It uses a peeling/unpeeling concept through its compliant adhesive feet. The compliant adhesive

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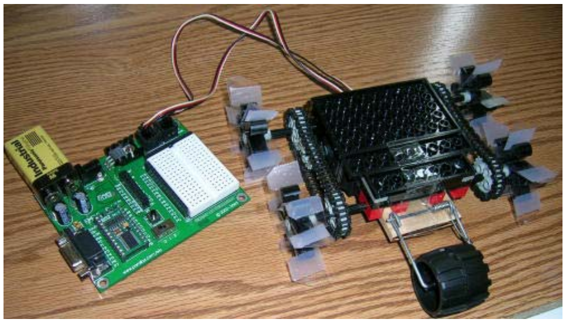


Figure 1 The prototype of geckGO

feet are achieved through specially designed spoke-wheels with partially curved rims and ordinary office tape. A preloading tail is integrated into the main body for agile and stable climbing. Two Parallax© motors are used for driving and steering. The autonomous ability is gained through the Parallax© microcontroller, Basic Stamp II. The main body is constructed with LEGO© parts. Except for the specially designed feet, all the other components of geckGO are inexpensive educational parts. One of the goals of developing this prototype is to provide us and other researchers with an easy-to-implement test bed for bio-inspired climbing robots and dry adhesive technology. The design, analysis and experiments of geckGO are detailed in the following sections.

II. GECKGO DESIGN AND IMPLEMENTATION

By reducing the robot's materials to their basic forms and utilizing systematic approach, this autonomous robot may serve as a foundation for the further study of gecko related technology. Presuming a robot with standard components and an easy modular design can autonomously maneuver across horizontal, oblique, and vertical planes, the possibilities for more intricate and multifarious designs seem endless. If grips made of ordinary office tape are enough to hold the robot in place and allow for smooth, functional motion, then synthetic dry adhesive pads would undoubtedly be an effective component for robots with a vast potential of commercial implementation. The geckGO serves to prove that said robots are a practical, promising form of new technology.

A. Inspirational Background

Though several species of geckos exist, and vary in sizes, shapes, and weights, all are capable of walking on several types of surfaces by way of their very special toes. Geckos can walk on inclined planes, vertical surfaces, and even upside-down without using chemical body secretions or surface tension. Their dry adhesion comes by way of van der Waals forces generated between a surface's microscopic imperfections and the gecko foot's thousands of setae, subdivided into mil-lions of spatulae [12]. A quick curling and uncurling of the toes and their corresponding fibers characterize the gecko's unique walking ability. Such a natural phenomenon has sparked the intrigue of researchers across the world.

Some efforts are being made to recreate the gecko foot geometry in synthetic form [9][13][14]. These endeavors are executed in an effort to manufacture the world's first dry adhesive. This adhesive would, theoretically, be self-cleaning and require no energy to maintain attachment. The hold would

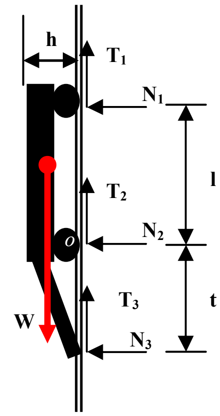


Figure 2. Free-Body Diagram of the geckGO

be strong, and removal (without residue) would be only a peel away. Dry adhesion relies mainly on physical shape and con-tact area, not surface material or atmosphere. Thus, dry adhesion patches could be used in a vacuum, in space, under water, or in normal daily human environments [9].

With the above biological inspiration and the concept Mini-Whegs™ [8], we have developed geckGO. Simple modular designs have been considered and adapted for this robot. Additionally, several key design improvements and new additional features have been included to enhance the robustness and effectiveness of the robot's wall-climbing abilities. GeckGO serves to suggest that if the technology and innovations present within this small robot allow it to ascend walls with office tape as the only means of adhesion, a future fusion with dry adhesive products could lead to a new generation of wall-climbing robot with vast capabilities.

B. Major Components and Specifications

The major components of the geckGO are: 2 Pa-rallax Servo Motors, 1 Parallax Board of Education, 1 Parallax BSII microcontroller, several LEGO© parts, 4 specially designed compliant spoke-feet, a preloading tail, tape, and a 9 Volt battery.

The framework of the geckGO measures 8 cm x 8 cm x 3 cm (length/width/depth) without a tail, and 15 cm x 8 cm x 3.5 cm with a tail. The feet and axles ex-tend the overall dimensions to 16 cm x 17.5 cm x 3.5 cm (6.5 cm wheelbase). The whole robot weighs approximately 195 grams, which does not include the 90 gram Board of Education and the 50 gram 9 Volt battery. The robot was constructed in an effort to minimize all dimensions given certain component constraints, such as the size of the Servo Motors. The geckGO boasts 4 compliant 6 spoke-feet, each with its own axle. The two motors each drive a front and rear foot on their respective left/right sides. By adjusting the speed in which the motors rotate via Basic Stamp code, the robot is allowed to steer left and right.

C. Force Analysis

A simplified free-body diagram was constructed for the static analysis of the geckGO. Dynamic factors were omitted in order to demonstrate the relationship between certain robot characteristics while it is either on a vertical plane or moving very slowly. The normal and tangential forces produced by the feet and tail are assumed to act at single respective points on the wall.

Fig. 2 represents a free-body diagram of the forces present when the geckGO is stuck to a vertical wall via the adhesive tape present on its 4 feet. Normal (N) and tangential (T) forces on the vertical wall are shown at each point of application, 1, 2, and 3. W represents the weight of the whole robot at its center of mass, while h is the height above the surface on which it rests. Distances l and t locate the three points of contact at/from point o.

With the sum of the moments around point *o* set equal to zero, and the counter-clockwise direction considered positive, equation 1 results.

$$Wh = N_1 a + N_3 t \tag{1}$$

Considering the tangential adhesive forces inherent within the tape on each foot are enough to counteract the weight of the robot, the normal forces remain as the governing factors for successful vertical climbing functionality [8]. Rearranging the variables in equation 1 yields equations 2 and 3.

$$N_1 = \frac{Wh - N_3 t}{a} \tag{2}$$

$$W = \frac{N_1 a + N_3 t}{h} \tag{3}$$

For the purpose of evaluation and comparison, these equations clearly lay out the relationships between normal forces, weight, effective height of the robot, wheelbase, and tail-force application distance. More specifically, equation (2) suggests that the apparent normal force at point 1 decreases with the presence of a preloading tail and its subsequent N_3 normal force. This decrease is also a function of the length of the tail, *t*. Similarly, as shown in equation 3, the maximum allowable weight is also increased as a result of the presence of a tail.

Furthermore, it may be said that the normal force at point 1 decreases as the wheelbase increases and the maximum allowable weight increases as the effective height of the robot decreases. These assessments certainly factor into the dimensional design of the robot; however, greater precedence is given to component space-necessities, overall volume and weight minimization, and manufacturability. Ultimately, a seemingly optimized design was settled upon.

D. *The Theory and Design of Compliant Feet*

The design of the geckGO's feet is inspired by the biological research conducted on the gecko, specifically the motion of its toes during each step. The *curling/uncurling* action of the gecko toes suggests that the adhesive on each foot should mimic this behavior by way of a similar *peeling/unpeeling* stroke. Generally speaking, an adhesive such as office tape is capable of withstanding a great amount of normal and tangential forces. This resistance, though, is significantly decreased when small areas of the tape are progressively peeled off at smaller angles, again, in a manner much like the curling of the gecko toes. Converting these theoretical concepts into physical design is accomplished through the proposal of a spoke-wheel with a partial curved outer rim. Each spoke would essentially act as a single step of a gecko foot, continuously making contact with the surface as its central axle rotates. See Fig. 3.

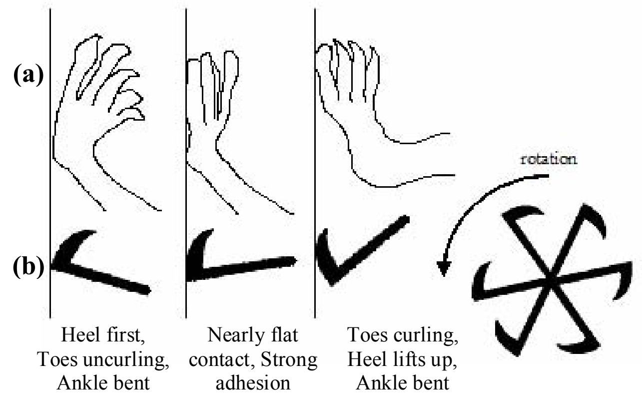


Figure 3. (a) Gecko foot/ankle and (b) Spoke-wheel climbing motion visual comparison

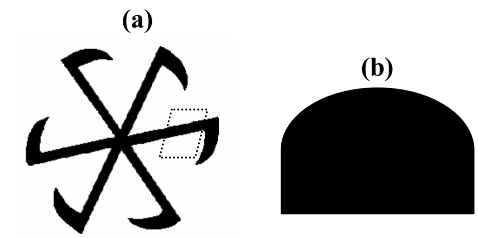


Figure 4. geckGO preliminary foot design, (a) side view and (b) spoke profile

In both the gecko step and the motion of the spoke-wheel, the heel makes first contact with the walking surface, as the toes begin to uncurl. Greatest adhesion occurs when a majority of the foot makes contact with the wall. To remove the foot, the toes are curled up as the heel and foot are lifted away from the surface. The repetition of this process produces a fluid walking motion. Furthermore, using a compliant material, such as Delrin®, enables the contact heel to bend under force, comparable to the bending of a gecko's ankle joint.

Existing models of wall-climbing robots make use of 3 or 4 spoked appendages. Their creators have found that an increased number of spokes results in less required elastic bending within the ankle [8] [9]. This concept was advanced in the design of the geckGO. A total of 6 spoked appendages, one every 60° of rotation, comprise each of the 4 feet on the geckGO. These added spokes provide a greater amount of adhesive tape contact area to stick to the wall surface at any given time. This adds to the overall strength of the robot, reducing the possibility of slipping. This added stability is further increased by having the front and rear feet, on the left and right sides of the robot respectively, offset from each other 30°.

The geckGO preliminary foot design, shown in Fig. 4, is oriented in a way such that, during foot rotation, the adhesive tape attached to the foot appendages comes in contact with the wall surface, sticks, then wraps around the heel and along the sickle-like outer rim. Having the heel, as opposed to the toe, make con-tact with the surface first adds greater robustness to the robot. A heel first design is better suited to overcome

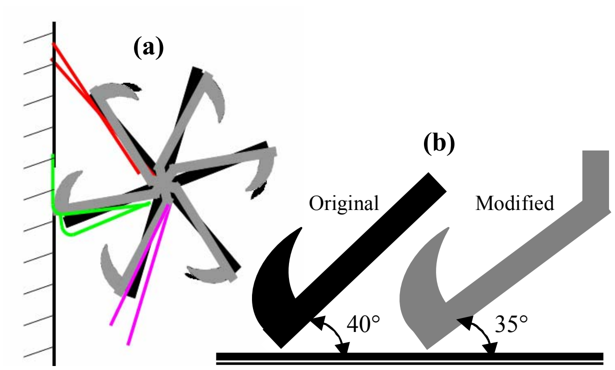


Figure 5. (a) Superimposed wheel designs and (b) tape application angle comparison

surface obstacles and more closely resembles the physics of natural walking in both geckos and humans alike.

Moreover, the heels and rims of the geckGO feet are uniquely designed in a smoothly curved manner. This curved design coincides with the intrinsic flow of the rotating wheel. As the foot-wheel rotates and the tape wraps around the heel towards the toe, the curvature facilitates a natural peeling motion. This motion is obviously desirable given the guiding principles surrounding this type of robot.

Another feature exclusive to the geckGO feet is the incorporated contour profile spoke geometry. Pictured in Fig. 4, the rounded cross-section of each spoke/leg automatically curves the tape attached to it. In doing so, the tape stiffens, which ultimately allows for consistent tape application. Without said stiffening, the tape is likely to be applied in an uneven, unpredictable manner. The augmented profile allows the uppermost part of the curve to make first contact with the wall surface and progressively apply the rest of the adhesive strip. Smooth, consistent tape application promotes a strong-er, more firm attachment and better performance results. Existing robot prototypes use rolled up pieces of tape to alter leg-profiles [8]. The geckGO incorporates this concept into its original design. By doing so, the feet may be manufactured consistently, each spoke having the exact same pre-stiffening curve.

With the general guidelines and components of the geckGO feet decided upon, improvements may be made. Using the original design as a foundation, an improved design is developed. This improved design takes each spoke and bends it at an angle of 45°. Each bend occurs at a point approximately 0.75 cm measured radially from the center axis. Since all 6 spokes are identically angled, there still remains one spoke per 60° of rotation. The benefit of angled spokes lies in the tape application angle. Smaller angles result in a smoother, more consistent application, which in-creases the strength of the hold. For conceptual purposes, consider applying tape to a surface at near orthogonal angles, as compared to a nearly horizontal, small angled, application. Clearly the small angled application results in a flatter, more even attachment.

Fig. 5 visually compares the original (black) and improved (gray) feet designs. Given equal lengths of tape, the graphic clearly displays the decreased tape application angle present within the improved design. In this case, the angle was reduced

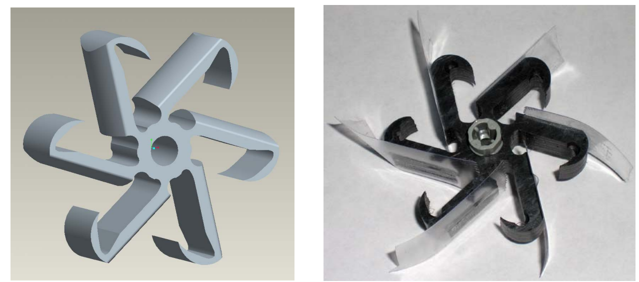


Figure 6. (a) 3D CAD modeled foot (b) Fully manufactured foot with axle and tape

Figure 7. Fully assembled preloading tail

from 40° to 35°. Considering both the original design and the 4 spoked Mini-Whegs™ have a 40° tape application angle, experimental analysis has shown that the improved design demonstrates progress over its precursors. The 3-D CAD model and the prototype of the compliant feet are illustrated in Fig. 6. The prototype is made of Delrin® and machined by a CNC milling ma-chine.

E. Adhesive Selection

As previously mentioned, one of the goals of the geckGO is to have it climb a wall using ordinary office tape. This tape must be strong enough to hold the robot on vertical surfaces at each of its contact points. The tape must also have a firm hold at its attachment points on each of the 6 spoked appendages of every foot. Considering the wall and spoke attachment surfaces are located on opposite sides of the tape, double-sided tape seemed most applicable. Scotch® brand *Permanent Double Sided Tape* was tested and ultimately deemed a good option for use. Furthermore, Scotch® brand *Magic™ Tape* was placed over a small section of each double sided tape overhang (sticky side down) in order to keep the double sided tape from sticking to the heel of each foot during each unpeeling phase.

F. Preloading Tail

As mentioned in section II-C, the apparent normal force at each of the front-most feet decreases with the presence of a preloading tail and its subsequent N_3 normal force. In order to apply a constant force, regardless of the direction of motion or gravity, a mouse trap design was incorporated. The design was constructed using the base, metal appendage, and one springarm from a Pic® brand mouse trap. A wide LEGO© wheel uses the metal appendage as an axle, effectively forming the geckGO's preloading tail. Fig. 7 shows a picture of this design. Overall, the tail serves to lessen the normal forces required of the robot to overcome the hold of the tape, as well as to provide added stability for the prevention of robot toppling. This tail was modeled after and closely mimics the behavior of a gecko's tail in that it provides added stability and reduces normal forces while walking.

G. Autonomous Propulsion and Steering

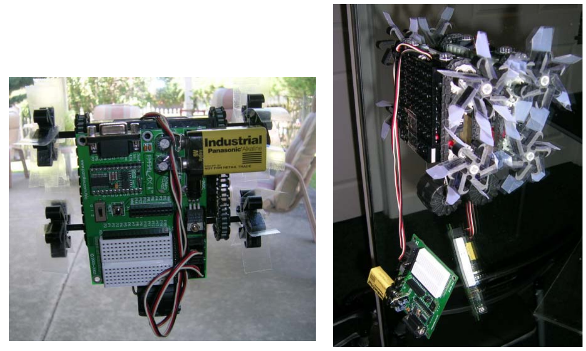
GeckGO propulsion is achieved by way of two Parallax Servo Motors, gears, gear chains, and axles. Having two motors marks an improvement over previous models, considering steering may be achieved in a simpler and more efficient manner. Each motor is controlled via a Parallax Basic Stamp II. Since the rotational speed of each motor may be modified, controlled steering is attainable so long as the robot is moving forward. The robot may be controlled to crawl left or right by speeding up the appropriate motor and slowing down the other. No complex steering mechanisms (like a rack and pinion setup) are necessary; only code alterations are needed.

III. EXPERIMENTS

All experiments occurred in room temperature environments on smooth, flat surfaces. Preliminary trials used two piece LEGO© components attached by way of a screw directly into each motor. However, this design simply did not provide the torque necessary to allow for vertical climbing; the screws kept loosening as a result of the excessive torque. Accordingly, the design was modified to incorporate a cut-down version of the gear shaft cap that comes with each motor. A LEGO© gear was then wired and hot-glued to this shaft cover to create a much more robust drive train. This new design worked very well, providing all the torque necessary for the robot to ascend a wall as demonstrated in Fig. 8.

Throughout several tests, the geckGO displayed its ability to traverse horizontal, angled, and vertical surfaces. The robot was able to steer (via motor control) and walk up, down, and sideways on each of these surfaces. Given the main programmed Basic Stamp code, the geckGO traveled at an average speed of 1.89 inches per second. This speed, though, could be adjusted via the code. Vertical distances traveled were limited by the 5 foot tall window and the 6 foot tall mirror that the robot was tested on. Even so, with several position resets, the robot was allowed and able to continue its forward motion trek.

After a long period of climbing, the geckGO often encountered its main mode of failure—tape failure. Due to the unavoidable dust and dirt in the air and on the climbing surfaces, the climbing tape inevitably lost its adhesive strength, causing the robot to fall. By way of an extremely careful and tedious process, the tape had to be replaced on several occasions. Each new application though, brought about continued success. Other occasional modes of failure included toppling due to a motion-induced weight shift, tape loss to the surface, temporary torque overloads, and improper gear shifting.



(a) (b)

Figure 8. GeckGO ascending a vertical (a) glass (b) mirror

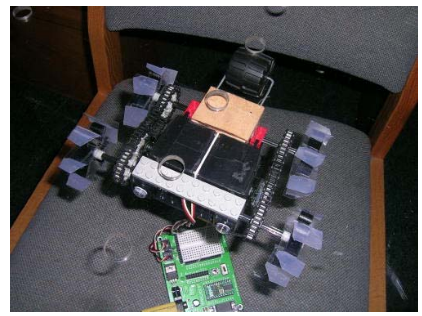


Figure 9. geckGO completely inverted, hanging from a horizontal surface partially supported by a chair

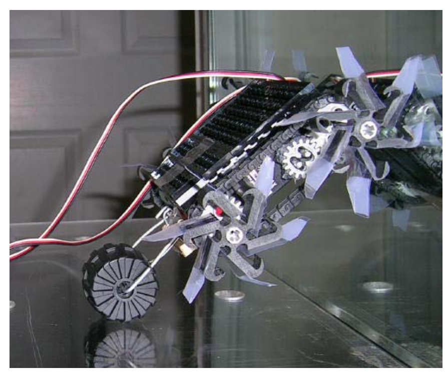


Figure 10. geckGO making the transition between orthogonal surfaces

In addition to the aforementioned climbing success, the geckGO managed two more noteworthy feats. The first entails the robot walking completely inverted on a horizontal surface. Shown in Fig. 9, the geckGO walked across a Plexiglas surface completely upside down, without falling. The second feat occurred when the geckGO repeatedly made the orthogonal transition between a horizontal and vertical surface. The transition was smooth and largely facilitated through the use of the supportive mousetrap tail. See Fig. 10 for a visual.

IV. CONCLUSIONS

A working, proof-of-concept robot (named geckGO) that can walk up, down, and sideways on walls was successfully developed. Given the simplicity by which the robot was conceived, the geckGO's notable feats mark tremendous achievement. With specifically designed compliant adhesive feet, two motors, some gears, and a preloading tail, the robot consistently climbs walls until its adhesive tape loses its bonding integrity. By no means flawless, the geckGO does display the art of simplicity, and a promising advancement for future robotics and other gecko-inspired developments.

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