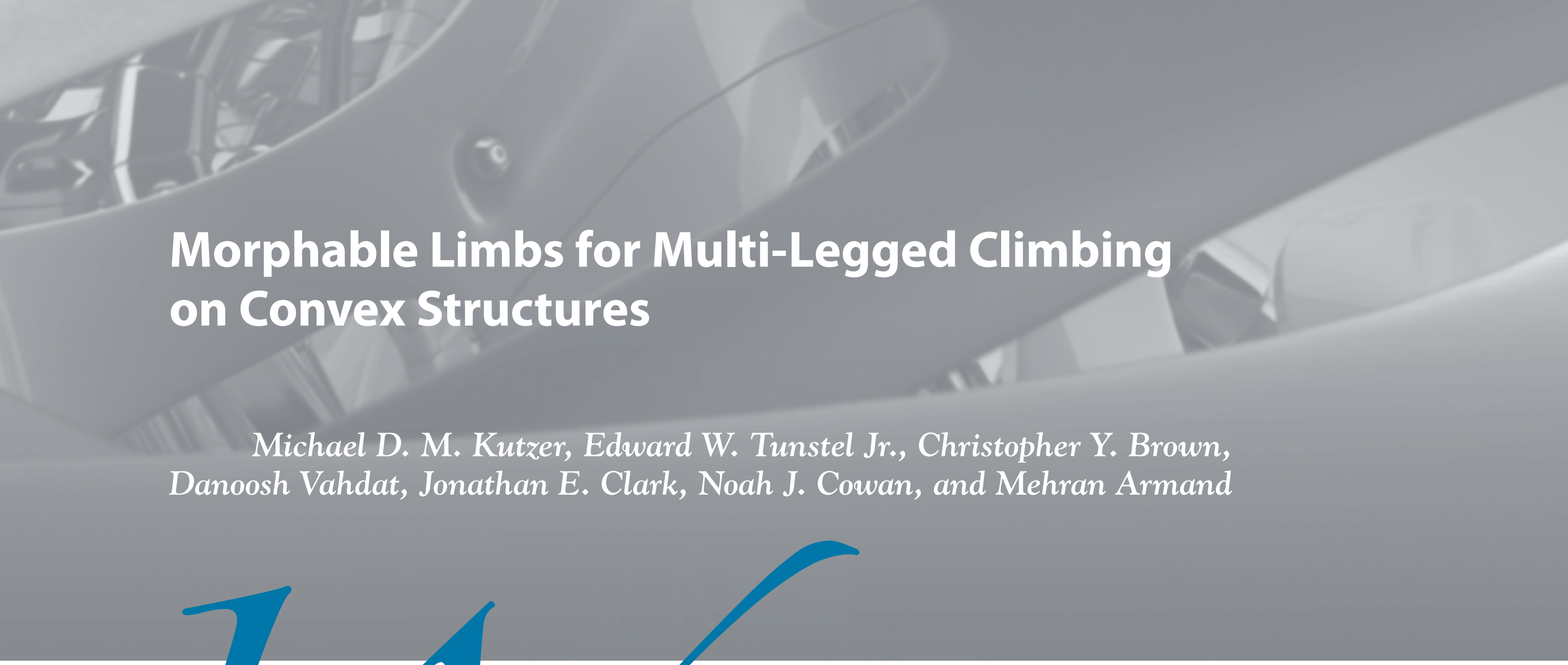

Morphable Limbs for Multi-Legged Climbing on Convex Structures

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We present a biologically inspired morphable mechanism for a small multi-legged robot and characterize the mechanism for statically stable climbing up convex/cylindrical structures. The design includes an analysis of the robot's static stability while climbing such structures. Preliminary experimental results highlight the merits and limitations of the overall approach.

INTRODUCTION

Robots with climbing mobility in structured and unstructured environments remain a focus of research aiming to achieve robust or general capabilities for a range of missions.[1–3] In this article, we focus on the narrowly defined problem of using a robot to climb convex structures such as utility poles and trees.[4–6] Such climbing machines would afford a wide range of possible practical applications, such as power grid maintenance and bridge inspection.[7–9] Moreover, the problem is defined narrowly enough to enable a principled design approach.

Finding ways of climbing convex structures presents a host of challenges for the research community. This article focuses on a biologically inspired, morphable mechanism and associated robot for climbing known convex/cylindrical structures in man-made environments (e.g., pipes, electrical conduits, small pillars, chair/table legs, large ropes, large wires, etc.). We envision that the approach defined in this article would also be applicable to locomotion on natural surfaces, such as trees, with modest additional development. Specifically, we present and characterize a climbing approach inspired by simple observations of beetle climbing behavior.

This article focuses on small robots that climb using a set of morphable limbs. In this context, morphable limbs refer to legs with many degrees of freedom. Constraining the operating criteria to be specific to convex/cylindrical structures permits simplification of the overall problem. Specifically, studying this subset of structures makes it feasible to rely solely on simple friction interactions rather than requiring advanced materials, microspines, or both [e.g., as used on existing systems such as RiSE (Robotics in Scansorial Environments), StickyBot, or SpinyBot systems].[10–12] We present simple principles and equations for statically stable climbing by a multi-legged robot with morphable limbs. Preliminary experimental results suggest the strengths and limitations of the overall approach.

BACKGROUND

Researchers have proposed a number of robot designs and prototypes that are capable of locomotion on convex/

Figure 1. Images illustrating experimental observations of a beetle climbing a thin straw using a "hugging" gait.

cylindrical structures. For example, Chatzakos et al.[13] developed a robot for omnidirectional locomotion on pipe exteriors for inspection tasks. The robot exploits features of the pipe, such as metal insulation strips to which the robot can attach via a clamping mechanism. Esponda[14] presented a design for a rope-climbing robot capable of detecting a rope and grabbing onto it to climb up and down between a floor and ceiling. Fauroux and Morillon[6] developed a robot capable of climbing elevated tubular structures commonly found in urban areas, such as poles, lampposts, and water pipes. Their system uses rollers for vertical climbing and a self-locking mechanism to avoid energy consumption while stationary on the structure; initial experiments demonstrated stable vertical climbing. Additional concepts are surveyed in Ref. 1, which covers systems that are mostly applicable to climbing on planar surfaces. Biologically inspired solutions for a range of climbing tasks are covered in Ref. 2.

The literature includes substantial results from biologically inspired robotic systems focused on mimicry of various insects and animals. This article turns its primary focus to the characterization of climbing aspects of locomotion as inspired by qualitative features of beetle climbing behavior. We instantiate these qualitative observations in a newly designed set of morphable limbs. A unique feature of the robot described in this article is its ability, using morphable legs, to climb convex structures common in the interiors of buildings. We would expect this approach to apply, with little modification, on certain vertical and inclined structures in the natural environment.

MORPHABLE LIMB FOR CLIMBING LOCOMOTION

We observed qualitatively that beetles, when climbing relatively small grasses and stalks, use a "hugging" grip to maintain sufficient climbing forces (Fig. 1). Additionally, they appear to use a "hug-shimmy-hug" gait to traverse upward. Using this beetle climbing behavior as inspiration, we investigated leg designs that would enable the robot to conform to the outer surface of the structure of interest. Our proposed solution involves a simple cable-driven "pull-pull-pull" system capable of wrapping around structures using varied cable actuations. Individual rigid vertebrae are spaced along a thin superelastic nitinol rod. This rod maintains spacing between vertebrae while allowing the overall structure to flex in response to tensioning cables and interactions with the environment. An alternative mechanism, designed for medical applications, that also relies on drive cables and elastic deformation of superelastic nitinol is described in Ref. 15. Representative climbing concepts are depicted in Figs. 2a and 2b. When considering this type of articulated leg, additional climbing methods, such as the capability to traverse within hollow structures, can also be imagined.

Characterization of Symmetric External Climbing

As a preliminary effort, we consider the robot climbing a straight cylinder such as a pipe. Given this simple structure, and assuming a multi-legged robot with legs offset sufficiently to enable overlapped wrapping, we see that formulation of the climbing problem can be simplified to consideration of a set of basic parameters. For sim-

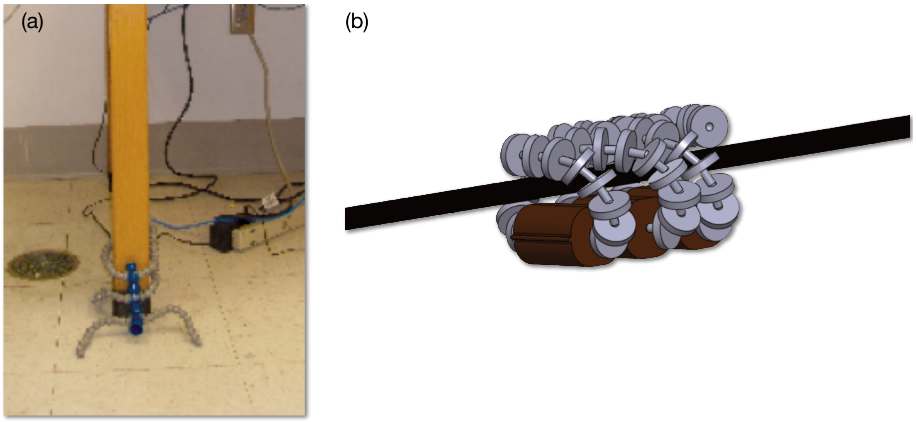

Figure 2. Morphable manipulator-based climbing concept: (a) initial proof-of-concept test bed for qualitative static stability investigation; (b) traversing a thin wire.

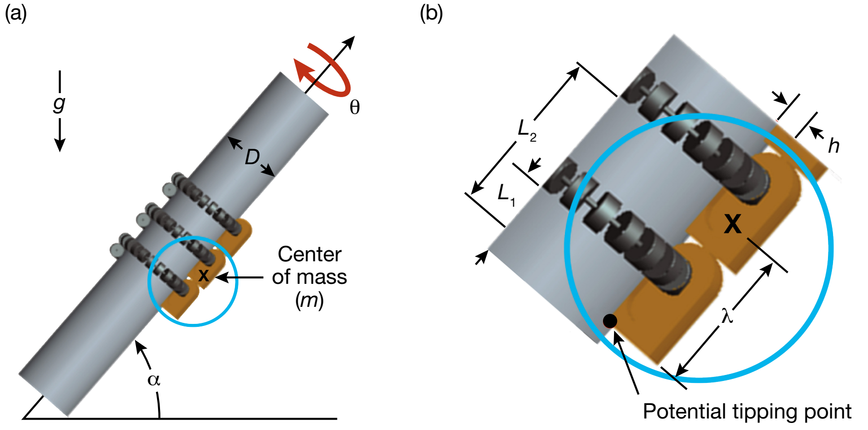

Figure 3. (a) Identification of climbing parameters of the cylindrical climbing surface; (b) robot characterization parameters. Note that, for the definition of the potential tipping point, the robot is assumed to be in a hanging configuration on the pipe.

plicity, we reference robot-specific terms relative to a potential tipping point on the robot. To define this tipping point, we assume that the robot selects an orientation on the underside of a pipe (i.e., it hangs below the pipe for all non-vertical pipe orientations). Using this point, illustrated in Fig. 3, we define the lengths L_1 and L_2 as the distances between the mean position of pairs of legs and the tipping point (a third length, L_3, can be defined in a similar fashion, measuring from the tipping point to the forward leg). Additionally, the system center of mass is defined using λ as the axial offset from the tipping point and h as the offset from the pipe wall perpendicular to the pipe axis. The pipe itself is characterized by a rise angle, $0° < \alpha \leq 90°$ defined above the horizontal, and a diameter D. With these parameters, and assuming that the robot's movements are sufficiently slow to treat the system as effectively static, we see that the minimum friction force to keep the robot from sliding down the pipe is defined as

$$F_{slide} = mg\sin(\alpha), \qquad (1)$$

where m is the robot net mass, and g the acceleration due to gravity. Likewise, the minimum torque required to keep the robot from tipping is defined as

$$\tau_{tip} = mg(h\sin\alpha + \lambda\cos\alpha). \qquad (2)$$

In the plane orthogonal to the cylinder axis, we add an angular offset parameter $-90° \leq \theta \leq 90°$ to define the robot's effective orientation on the pipe. Using this term, we introduce a minimum required torque to keep the robot from twisting or rolling on the pipe as

$$\tau_{roll} = \left(\frac{D}{2} + h\right)(mg\cos\alpha\sin\theta). \qquad (3)$$

Assuming that the robot is symmetric in the plane orthogonal to the cylinder axis, we introduce a single term, w, to describe the robot's body width, which, given the pipe diameter, corresponds to a term that we will refer to as the angular width of the robot (Fig. 4),

$$\beta = \tan^{-1}\frac{2w}{D}. \qquad (4)$$

Assuming a leg consisting of m discrete, evenly spaced elements, we introduce parameter γ to describe their angular displacement when wrapped around a pipe (Fig. 4b) and defined as

$$\gamma = \tan^{-1}\frac{2\nu}{D}, \qquad (5)$$

where ν represents the linear spacing between leg elements on an uncurved leg.

Using these parameters, we can calculate the net force for each pair of legs as

$$F_{legs} = -2\sum_{i=1}^{m} N_i\cos(\beta + i\gamma), \qquad (6)$$

where F_{legs} is defined in the opposite direction of N_{body} shown in Fig. 4b. In Eq. 6, N_i represents the normal force of the ith segment of the leg. The term N_{body} repre-

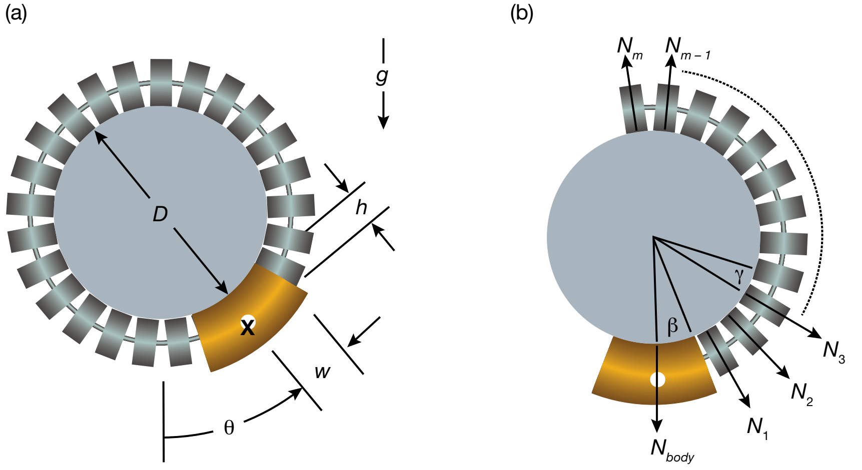

Figure 4. Robot characterization in the plane orthogonal to the cylinder axis. Parameters that affect the roll of the morphable leg are shown in panel a, and the force distribution of the leg segments on the pipe is depicted in panel b.

sents the net normal force seen by the body of the robot. Applying these fundamental equations, we see that for our system to maintain static stability, the following net force would apply for a set of paired legs:

$$F_{legs} \le 2\sum_{i=1}^{m} N_i \cos(\beta + i\gamma) + 2\mu \sum_{i=1}^{m} N_i \sin(\beta + i\gamma). \quad (7)$$

Here, μ represents the coefficient of static friction between the leg and climbing surface. Although this relationship is potentially useful, not all terms used can be readily defined or measured using onboard sensors and environmental understanding. Specifically, defining the relationship between segment normal forces (N_i) and applied cable tensions requires experimental testing.

Preliminary Test Results

A preliminary prototype integrating a superelastic nitinol backbone with a series of 12 evenly spaced commercially available shaft couplings was used to evaluate the feasibility of climbing using this basic approach. To evaluate force distributions of the elements of the leg, FlexiForce pressure sensors were mounted along the outside of two pipes of different diameters, 2.375 in. (~6 cm) and 4.3125 in. (~11 cm). As shown in Fig. 5, the sensor spacing ensured that vertebrae of the leg would interact roughly with the center of each force sensor.

Preliminary pressure-testing results show a nonuniform distribution of forces around climbing surfaces (Fig. 6) and an inverse relation between cable tension and robot angular width on the pipe (Fig. 7). As shown in Fig. 5, a 12-segment leg is wrapped around a 2.375-in. pipe from the side starting in a vertical position. FlexiForce sensors are placed between the pipe and segments to measure contact force. Cable tension is then applied, starting with 1 lb of tension and increasing in intervals of approximately 1 lb until 11 lb of tension is reached. As the cable tension is increased, the change in contact force distribution is measured (Fig. 6). Green bars represent both the assumed (normal) direction and relative magnitude of the contact force.

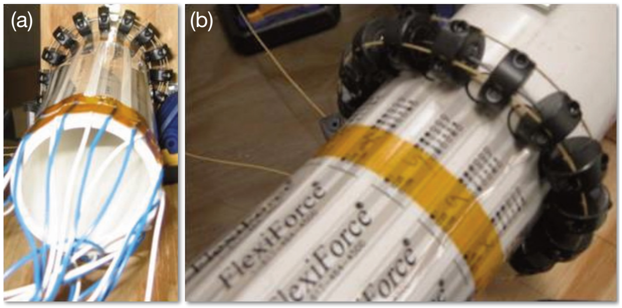

Figure 5. Force distribution testing with pressure sensors and morphable leg wrapping around the 2.375-in. pipe.

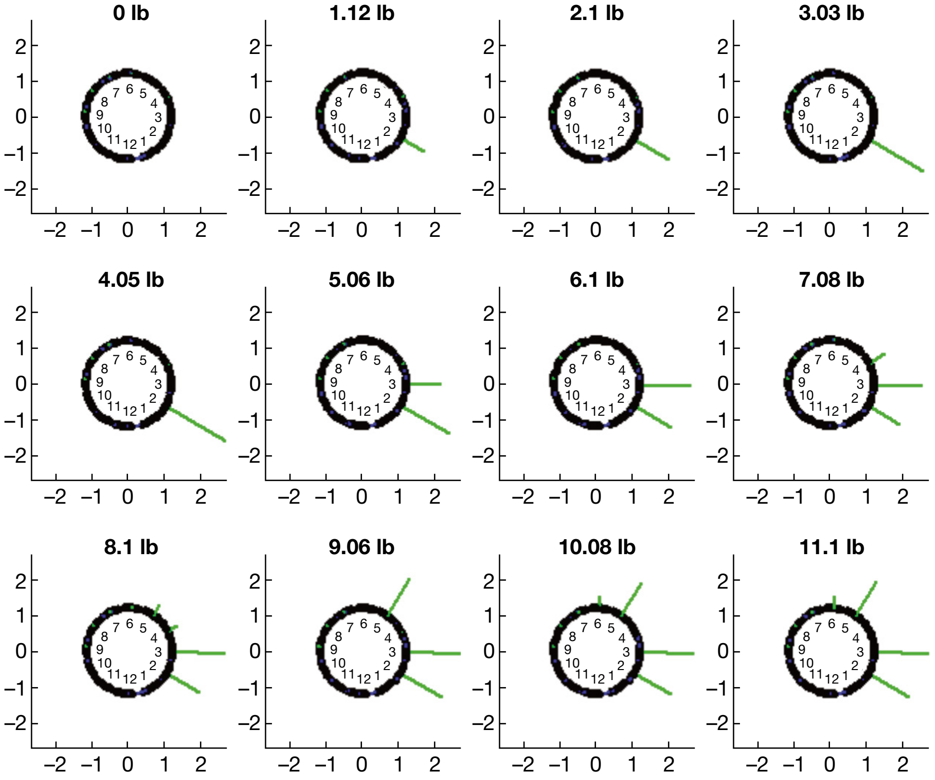

Figure 6. Contact force distribution as a function of drive cable tension.

To quantify the potential for climbing, Fig. 7 shows the body angle (β, Eq. 4) required to achieve a non-zero lifting force (i.e., a force pressing the body of the climber to the surface of the pipe) from the legs.

The results in Fig. 6 show that increased cable tension results in a more uniform distribution of contact forces along the pipe. Additionally, these data suggest that, given the current method of actuation, leg length should be reduced given the negligible contact forces of the latter segments of the leg (i = {8,9,10,11,12}).

Possible causes for the variability in segment contact forces for lower cable tensions include variance in tendon moment arms (due to manufacturing tolerances),

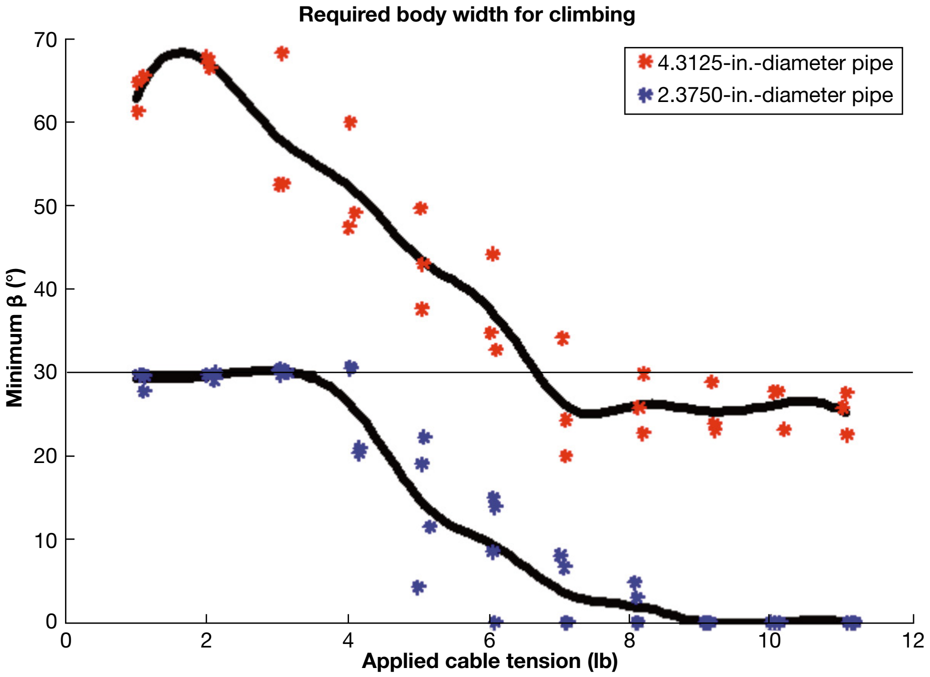

Figure 7. Processed force data showing the inverse relation between required cable tension and the robot's minimum required angular width on the pipe to achieve a non-zero contact force.

uneven curvature and buckling in the superelastic backbone, and unpredictable frictional effects between the tendon and segments. Some recommendations for future improvements include reducing cable friction through material selection, reducing the weight of individual segments to prevent uneven loading and buckling in the superelastic backbone, and improved manufacturing techniques for greater reliability.

Results from Fig. 7 suggest that a larger angular width (β, Eq. 4) is advantageous to climbing; however, this assumes that the body conforms perfectly to the pipe in question. Additionally, given the limitations of the current prototype leg, there is an apparent advantage to climbing small pipes.

These results also suggest that robot body mass must remain low for realistic climbing scenarios. Results will likely improve as a result of decreased cable friction effects to maximize the ratio between cable tension and contact force, designed asymmetry in backbone stiffness to encourage more evenly distributed contact forces along climbing surfaces, and optimization of leg segment geometry to improve contact force distribution.

These pressure test results show a clear relation between body angle (β, Eq. 4) and the required cable tension to achieve a positive holding force. These results collectively inform minimum next-step design decisions and functional requirements of a complete multi-legged robotic system based on morphable limbs.

CONCLUSIONS

A goal of this research is to realize robots with morphable limbs that are capable of agile locomotion in the plane, transition maneuvers from planar locomotion to climbing, and climbing on a variety of convex structures. Actively flexible leg designs that can morph to and generate forces necessary to adhere to various surfaces represent an advance beyond existing robotic models. Limitations of the actuation strategy, however, suggest that dominating friction forces and scaling may limit the current approach. Several technologies apply for candidate materials and actuation, such as electroactive polymers, shape memory alloy wires, and/or conventional tendon-driven structures with conventional DC motors. For real-time gait adaptation and feedback control, future plans consider integration of small-scale tactile sensors in the legs of the robot.

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REFERENCES

[1] Silva, M. F., and Machado, J. A. T., "Climbing Robots: A Survey of Technologies and Applications," in *Proc. CLAWAR*, Coimbra, Portugal, pp. 1–8 (2008).

[2] Habib, M. K. (ed.), *Bioinspiration and Robotics Walking and Climbing Robots*, InTech, Vienna http://www.intechopen.com/books/bioinspiration_and_robotics_walking_and_climbing_robots (2007).

[3] Chu, B., Jung, K., Han, C.-S., and Hong, D., "A Survey of Climbing Robots: Locomotion and Adhesion," *Intl. J. Precision Engrg. Manuf.* **11**(4), 633–647 (2010).

[4] Haynes, G. C., Khripin, A., Lynch, G., Amory, J., Saunders, A., et al., "Rapid Pole Climbing with a Quadrupedal Robot," in *Proc. IEEE International Conf. on Robotics and Automation (ICRA '09)*, Kobe, Japan, pp. 2767– 2772 (2009).

[5] de Bernardi, R., and da Cruz, J. J., "A Tree-Climbing Robot Platform: Mechanical Concept, Control Software and Electronic Architectures," in *Advances in Robotics, Automation and Control*, J. Arámburo and A. R. Treviño (eds.), InTech, Vienna (2008).

[6] Fauroux, J.-C., and Morillon, J., "Design of a Climbing Robot for Cylindro-Conic Poles Based on Rolling Self-Locking," *Industrial Robot: An International Journal* **37**(3), 287–292 (2010).

[7] Allan, J.-F., Lavoie, S., Reiher, S., and Lambert, G., "Climbing and Pole Line Hardware Installation Robot for Construction of Distribution Lines," in *Proc. 1st International Conf. on Applied Robotics for the Power Industry*, Montreal, Canada, paper 0707 (2010).

[8] Berns, K., Hillenbrand, C., and Luksch, T., "Climbing Robots for Commercial Applications—A Survey," in *Proc. CLAWAR*, Catania, Italy, pp. 771–776 (2003).

[9] Balague, C., Giménez, A., Pastor, J. M., Padrón, V. M., and Abderrahim, M., "A Climbing Autonomous Robot for Inspection Applications in 3D Complex Environments," *Robotica* **18**(3), 287–297 (2000).

[10] Kim, S., Spenko, M., Trujillo, S., Heyneman, B., Mattoli, V., and Cutkosky, M. R., "Whole Body Adhesion: Hierarchical, Directional and Distributed Control of Adhesive Forces for a Climbing Robot," in *Proc. IEEE International Conf. on Robotics and Automation (ICRA '07)*, Rome, Italy, pp. 1268–1273 (2007).

[11] Spenko, M. J., Haynes, G. C., Saunders, J. A., Cutkosky, M. R., Rizzi, A. A., et al., "Biologically Inspired Climbing with a Hexapedal Robot," *J. Field Robotics* **25**(4–5), 223–242 (2008).

[12] Kim, S., Asbeck, A. T., Cutkosky, M. R., and Provancher, W. R., "SpinybotII: Climbing Hard Walls with compliant Microspines," in *Proc. 12th International Conf. on Advanced Robotics (ICAR '05)*, pp. 601–606 (2005).

[13] Chatzakos, P., Markopoulos, Y. P., Hrissagis, K., and Khalid, A., "On the Development of a Modular External-Pipe Crawling Omni-Directional Mobile Robot," in *Proc. CLAWAR*, London, UK, pp. 693–700 (2005).

[14] Esponda, J. P. M., "Design and Construction of a Rope Climbing Robot," *CLAWAR*, Singapore, pp. 91–98 (2007).

[15] Kutzer, M. D. M., Segreti, S. M., Brown, C. Y., Armand, M., Taylor, R. H., and Mears, S. C., "Design of a New Cable-Driven Manipulator with a Large Open Lumen: Preliminary Applications in the Minimally-Invasive Removal of Osteolysis," in *Proc. IEEE International Conf. on Robotics and Automation (ICRA '11)*, Shanghai, pp. 2913–2920 (2011).

The Authors

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