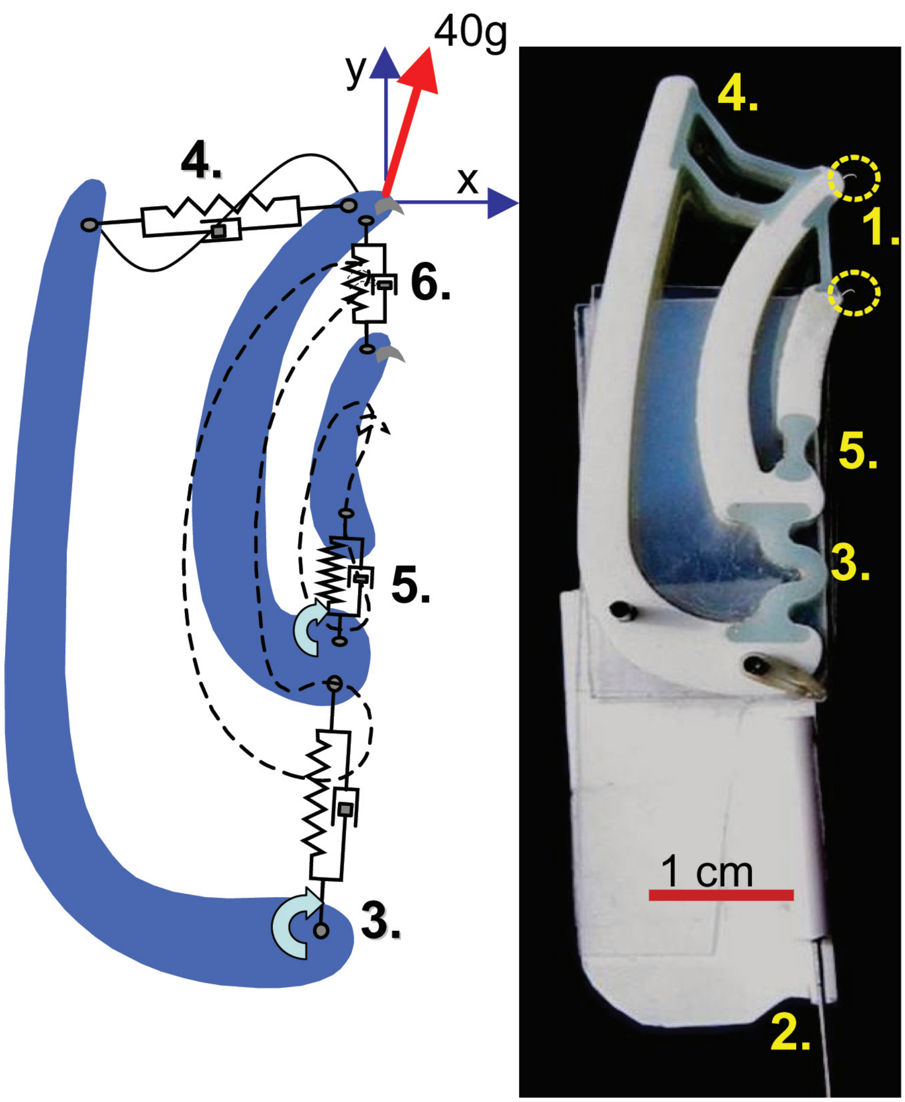

Figure 4.3: Photograph and equivalent elastic linkages for one toe of the climbing robot. Linkage at left shows the deflected position for a 40g load, superimposed on the undeflected position (shown in dotted lines). Key to labels: **1.** 200 mm diameter spines (inside dotted circles), **2.** tendon for applying loads, **3.** soft urethane flexure permitting travel in y direction, **4.** buckling flexures with large compliance value in the $-x$ direction under compression, lower compliance under tension, **5.** primarily rotational flexure for the proximal spine, **6.** buckling/lift-off flexure for proximal spine.

The mechanisms are created using a rapid prototyping process, Shape Deposition Manufacturing [92, 21] that permits hard and soft materials to be combined into a single structure. In the present case, the white and grey materials are hard and soft urethanes, of 75 Shore-D and 20 Shore-A hardness, respectively (Innovative Polymers Inc.). The resulting structure can be approximated as an elastic multi-link mechanism, as shown in Figure 4.3.

The spines are approximately 1.5 mm long with a 200 μm shaft diameter and 10-35 μm tip radius. They are embedded directly into the hard white links during the SDM process. The soft urethane flexures provide both elasticity and viscoelastic damping. They permit greater extensions without failure than miniature steel springs (as were used on some of the earlier foot designs).

Following the approach from Chapter 2, for small deflections, the linear and rotational compliance of each spine in the two-dimensional cartesian coordinate plane can be modeled using a 3x3 compliance matrix, C, taken with respect to a coordinate system embedded in the spine:

$$\begin{bmatrix} c_{xx} & c_{xy} & c_{x\phi} \\ c_{xy} & c_{yy} & c_{y\phi} \\ c_{x\phi} & c_{y\phi} & c_{\phi\phi} \end{bmatrix}$$

At initial contact, we require that c_{xx} be very big for displacements in the $-x$ direction, so that a large number of toes can conform to uneven surfaces without requiring a significant normal force. This is accomplished through the flexures at the end of the toe (labeled 4. in Figure 4.3), which are designed to buckle so that they have a very high compliance for $-x$ deflections. For small tensile loads on the foot (in the $+x$ direction), some toes will still be compressed from the foot's engaging motions. c_{xx} should still be big in this case so these compressed toes do not push the foot away from the wall. This presents a design compromise since a smaller c_{xx} will move the spines back to the wall more quickly if they should slip and undergo a "skipping over the wall" phenomenon. Finally, for large tensile loads, c_{xx} should be small so the toes can disengage from the wall. This is also accomplished with the flexures at the end of the toe.

Table 4.1: SpinybotII Toe Compliance Matrices

Outer Spine:

$$\begin{bmatrix} 6.612 & 0.725 & -0.0197 \\ 0.725 & 1.45 & 0.00209 \\ -0.0197 & 0.00209 & 1.11 \end{bmatrix}$$

Inner Spine:

$$\begin{bmatrix} 7.27 & 0.909 & -0.0312 \\ 0.909 & 6.36 & -0.00282 \\ -0.0312 & -0.00282 & 1.72 \end{bmatrix}$$

Units:

$$\begin{bmatrix} mm/N & mm/N & rad/N \\ mm/N & mm/N & rad/N \\ rad/N & rad/N & rad/Nmm \end{bmatrix}$$

C Matrix:

$$\begin{bmatrix} c_{xx} & c_{xy} & c_{x\phi} \\ c_{xy} & c_{yy} & c_{y\phi} \\ c_{x\phi} & c_{y\phi} & c_{\phi\phi} \end{bmatrix}$$

At the same time, c_{yy} should be moderate, as it represents a trade-off. A softer c_{yy} allows each toe to stretch more in the longitudinal direction to increase the probability that it will catch an asperity during the downward stroke of the foot; but if c_{yy} is too big, the mechanism will require an excessive stroke length to support a given load. In essence, these factors determine the "asperity search length" for the downward stroke of the toe. At the same time, c_{xy} should be small so that stretching in the y direction does not cause the spines to retract. The $c_{x\phi}$ and $c_{y\phi}$ terms should also be small and, preferably, slightly negative so that displacements in the x or y direction are not accompanied by anticlockwise rotations in the (x, y) plane that would lead to premature disengagement.

The compliance matrix C was measured on a Spinybot toe, for both the outer and inner spines, relative to the outermost hard member of the toe. The compliances were measured around an operation point of (-0.13cm, 0.13cm) in the (x,y) directions. The results are shown in Table 4.1, and they can be seen to generally correspond to the desired values as discussed previously.

The toe mechanism shown in Fig. 4.3 was also modeled using Working Model^{TM} software (MSC Inc.), and the various linear and rotational compliance elements were adjusted to match bench-top test results of SpinybotII toes. The results are summarized in Table 4.2. The mechanism is designed so that initial contact at the inner, or proximal, spine actually forces the distal spine slightly outward ($+x$ direction) to increase the probability that it will also contact an asperity.

Once one or both spines have contacted the wall, the toe can apply a force that

Table 4.2: Compliances and Damping Parameters for Toe Linkage

Location (numbered label, Fig. 4.3)	Parameter in kinematic model c = linear compliance element b = linear damping element c_t = rotational compliance element
3.	c = 16.7 mm/N b = 0.1 Ns/m c_t =2 rad/Nmm
4.	c = 1.11 mm/N in tension c = 20 mm/N in compression b = 0.02 Ns/m
5.	c =1 mm/N b = 0.001 Ns/m c_t = 10 rad/Nmm
6.	c = 16.7 N/mm b = 0.1 Ns/m

is mainly vertical, with a small inward ($+x$) component to help the robot climb. Fig. 4.3 shows the effect of a typical 40 gram load sustained by one toe in climbing.

4.4 Underactuated leg design

An important observation of agile scansorial animals like geckos is that they employ *multi-level conformability* (e.g. lamellae, toes, and limbs) and *redundancy* (multiple pads per toe, multiple toes per foot, and multiple feet in contact) for reliable climbing. The same principles have been found necessary for SpinybotII. Accordingly, the entire foot mechanism is mounted on a prismatic joint with an elastic suspension that allows it to move up to 1 cm in the distal ($+y$) direction (see Fig. 4.4). In addition, the entire foot assembly is spring loaded by a second elastic element behind the pivot, where it is connected to a rotary RC servo motor. The result is an under-actuated R-R-P serial kinematic chain that traces a loop trajectory, as shown in Fig. 4.4, when the servo motor rotates back and forth. After some experimentation, the best elastic elements were found to be 6.4mm diameter elastic bands commonly used for dental braces.

Following the framework introduced in Chapter 2, each SpinybotII leg is an underactuated linkage system. The first joint, θ_1, is rigidly attached to the R-C servo motor. The second joint, S_2, is a passive prismatic joint (an elastic band) as a part of the four bar linkage. This elastic band provides tension selectively according to the configuration. The third joint, S_3, is a prismatic joint that passively helps promote force distribution among the legs. The trajectory of the foot is generated by rotation of the first joint, in combination with contact forces. Unlike cursorial robots, climbing robots cannot produce large forces against the wall surface. Accordingly, the compliance in the normal direction must be high. In the case of SpinybotII, the second, rotary joint temporarily becomes a free joint at the start of the stance phase to accommodate this requirement. In Chapter 5, it will be seen that Stickybot exhibits a very soft, nonlinear compliance in the normal direction for the same reason.

The design of adaptive underactuated legs for climbing robots is closely related to adhesive or attachment properties of the feet. The spines exhibit a highly directional

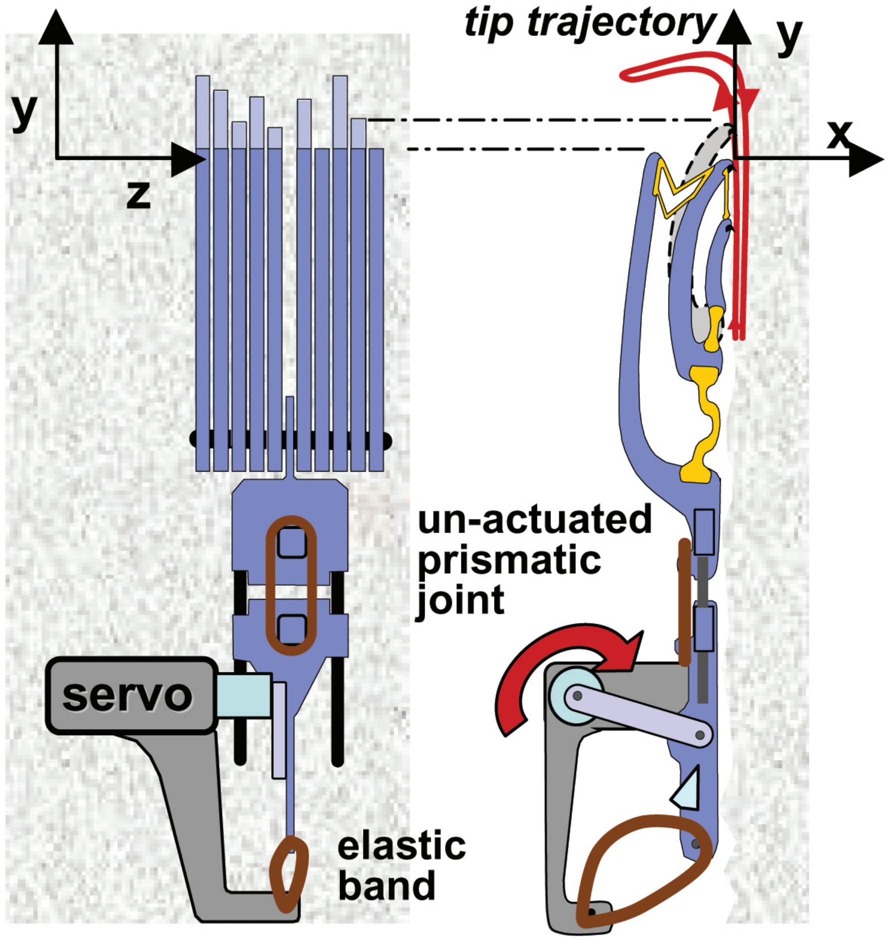

Figure 4.4: Side and plan view of one foot containing ten toes. The toes can deflect independently of each other. In addition, the entire foot can displace in the distal (y) direction due to an un-actuated prismatic joint.

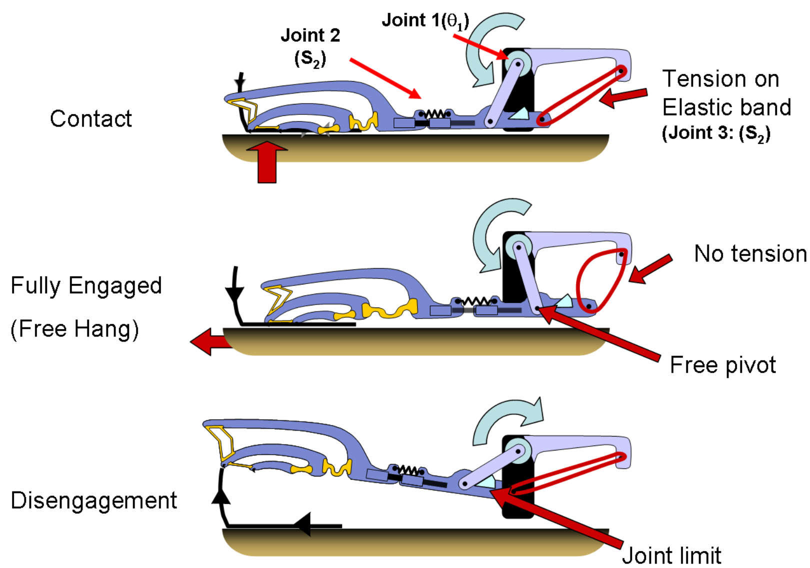

Figure 4.5: The sequence of motions is accomplished using an underactuated mechanism consisting of a single rotary RC servo motor and an elastic band that is taut while the foot is disengaged. **Top**: Tension in rubber band helps engagment of spines to asperities. **Middle**: When the foot is engaged, the loose elastic band prevents forces that would push the robot away from the wall. **bottom**: A hard stop causes the leg to lift off the wall as the servo rotates upward, with the elastic band keeping the leg pushed against the hard stop.

behavior; they generate large forces parallel to the wall and small inward forces when properly loaded. The SpinybotII leg is designed to utilize this directional characteristic to facilitate attachment and detachment. Upon engagement, the normal force is a function of the compliance in the leg and the preload of the elastic band. The compliance is high, so that minor variations in the position of the robot with respect to the wall produce only small variations in the normal force. Instead, the normal force is mainly a function of the preload in the elastic band, which is adjusted by choosing a band of a particular length and controlling the amount that it is stretched. Once the foot has engaged some asperities, the nominal trajectory of the foot deviates from unloaded trajectory resulting in forces.

The transition between one set of feet and the next is somewhat tricky. For secure engagement, the preload in the passive linkage plays a crucial role. However, this preload can cause the body to be pushed away from the surface after full engagement because previously attached feet become detached and stop providing a pull-in force. In Figure 4.5, the rubber band applies forces normal to the surface for only short period of time during engagement and becomes loose to remove undesirable reaction forces.

In summary, recalling the design process introduced in Chapter 2, we have several steps involved in designing the SpinybotII leg mechanism:

1. Identify desired behaviors of the designated mechanism

2. Identify desired norminal trajectory to acheive desired behaviors

3. Specify compliance matrices of points of interest along the trajectory.

The most important desired behavior is to achieve straight, stable and reliable climbing. This, in turn, requires (1) minimum reaction forces in the normal direction and (2) keeping the entire mass of the robot as close as possible to the wall at all times. In order to satisfy these conditions, the desired trajectory of the leg should be a nearly straight line along the wall. For this loaded trajectory, the desired compliance in normal direction to the wall needs to be large. (The actual SpinybotII leg has infinite compliance just after engaging the feet.) The compliance in the vertical direction, which is a combination of toe compliance is chosen to distribute the forces among the feet, especially when there is sudden movement such as slight slip.

The first joint, θ, has no compliance, and we have two compliant joints, S_2 and S_3. The Jacobian matrix for these joints is:

$$J = \begin{bmatrix} 0 & 1 \\ 13.3 & 0 \\ 0.133 & 0 \end{bmatrix}$$

The dimensions are mm for length and radians for angle. The compliance matrix at the desired configuration is:

$$C_j = \begin{bmatrix} 4.0 & 0 \\ 0 & 6.3 \end{bmatrix}$$

$$C = JC_jJ^T$$

$$C = \begin{bmatrix} 6.3 & 0 & 0 \\ 0 & 707.5 & 7.07 \\ 0 & 7.07 & 0.078 \end{bmatrix}.$$

In this leg compliance matrix, c_{yy} is much bigger than c_{xx}. This enables an extremely soft suspension in the normal direction to the wall so that the variation of the preload on engagment is small. As mentioned earlier, we tune the preload by changing the length and the pre-stretch of the rubber band.

4.5 Body Design: Promoting Load Sharing and Stability

The robot utilizes an alternating tripod gait, similar to that found in climbing insects (see Figure 4.6). At any time, the robot is ideally clinging by three feet. Like many climbing animals, the robot also has a tail which reduces the forces required at the front limbs to overcome body pitch-back from the wall. This pitch-back moment is produced by gravity acting at the center of mass, which is located approximately 2 cm

Table 4.3: SpinybotII Specifications

Mass	0.4 Kg
Max payload	0.4 Kg
Climbing speed	2.3 cm/s
Distance: COM to wall surface	2.0 cm
Batteries	lithium polymer total 340 mAh, 7.4 volts
Processor	40 MHz PIC
Servo motors (7 total)	0.37 Nm torque
Camera	0.02 Kg

outward from the wall. The weight of the robot, including lithium polymer batteries, wireless camera, and PIC microprocessor is 0.4 Kg. It can carry an additional payload of 0.4 Kg while climbing.

The climbing speed is quite slow (2.3cm/s) but can easily be improved upon with the addition of structural damping in the limbs and toe suspension. On initial contact of each foot with the wall, the spines and leg as a whole oscillate as underdamped structures. Such oscillations reduce the probability of engaging useful asperities as the spines are stroked along the wall. The addition of structural damping will greatly improve climbing performance and permit climbing at greater speeds. Higher performance motors may also be desirable.

While the main concern for vertical climbing is to avoid pitching back from the plane of the wall, it is also important to maintain rotational stability in the plane of the wall so that momentary slips to not become catastrophic. As seen in Figure 4.6 the center of mass of SpinybotII lies within a polygon of contacts when three feet are attached to the wall. If only two feet are attached, the center of mass generally remains within the polygon of contacts, due to the elongated body design. Also, as observed in climbing insects and reptiles, the legs have a slight inward pull toward the centerline of the robot. This arrangement reduces the upsetting moments (in the

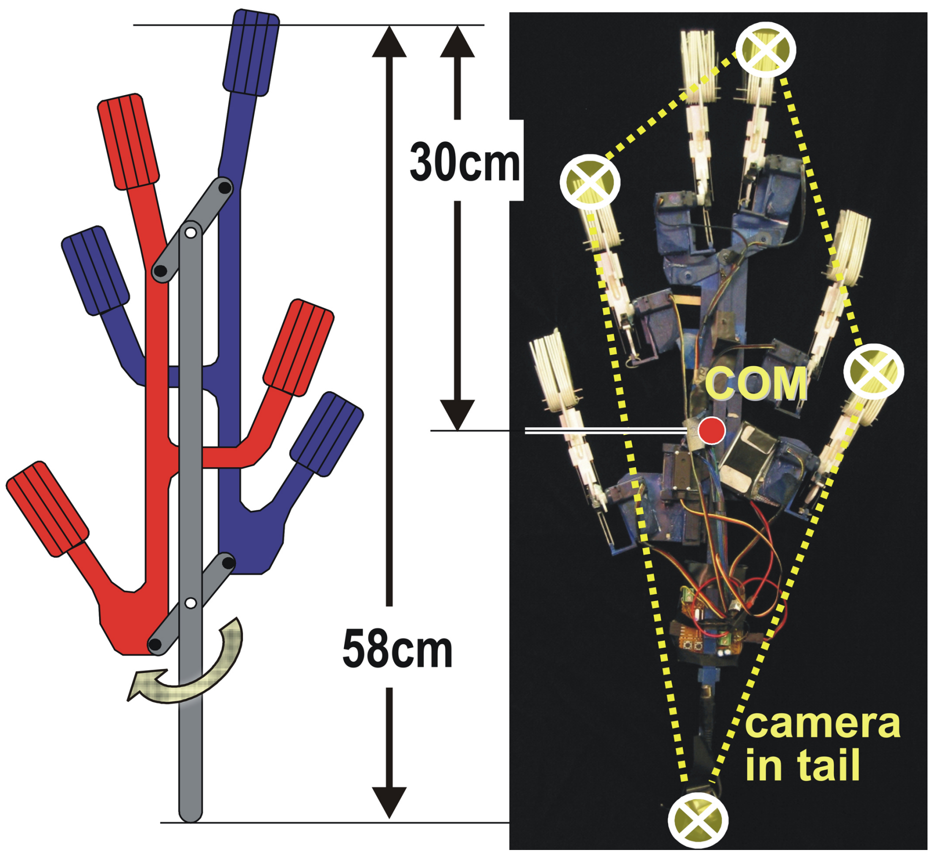

Figure 4.6: Photograph of SpinybotII wall and diagram of climbing mechanism. Each set of three legs is attached to a mechanism that allows the robot to “ratchet” its way up the wall with an alternating tripod gait. A long tail helps to reduce the pitching moment. The center of mass (COM) is within the polygon of contacts, to minimize yawing rotations in the plane of the wall.

Table 4.4: Effect of Scaling Parameters on Toe Compliances. Desired suspension compliances in the x- and y-directions (i.e., $1/k_{xx}$ and $1/k_{yy}$, respectively) vary as a function of robot weight, spine size and number of spines. The values in the table show how the compliances should be varied to maintain a constant x-direction compliance for the entire foot, and appropriate displacements in the y-direction, to engage most of the spines while not over-extending them. Usually the required number of toes n depends on the spine size, leading to $n \propto 1/r_s$ for a constant robot mass.

Compliance ($1/k$)	Normal Direction	Axial Direction
Number of toes n	~$1/n$	~$1/n$
Robot mass m	*constant*	~$1/m$
Spine tip radius r_s	*constant*	~r_s

plane of the wall) about the center of mass, should one of the legs momentarily lose its grip. If one of SpinybotII's three attached feet loses its grip, the robot will continue, usually only suffering from a slight change in heading; if multiple feet lose their grip it falls.

4.6 Discussion

SpinybotII climbs reliably on a wide variety of hard, outdoor surfaces including concrete, stucco, brick, and dressed sandstone with average asperity radii >25 μm. The essential principles behind its operation include using many miniature spines with a compliant suspension that ensures that the load is shared uniformly among them. The same principles can also be applied to larger robot platforms. Desired spine tip radius is a function of average asperity size for the surfaces to be climbed and not of robot size.

A more challenging problem is to tackle rough or corrugated surfaces or, in general, surfaces that have roughness comparable to spine length. Either the feet and toes must have enough "suspension travel" to accommodate the contours of the surface or they must have an additional active degree of freedom, like the toes of geckos or the tendon-actuated tarsus of insect legs. On contoured surfaces it should be possible to exploit internal "grasp" forces, in a manner similar to that used by robots that