Biological systems provide both great motivation by virtue of their striking performance, and guidance with the details of their actions. They are existence proofs that give us an indication of what is possible.

— Marc H. Raibert (1986)

3. Caterpillar Locomotion

This chapter presents the results of a brief study of caterpillars and their locomotion and relates the finding of this study to the structural design and motion programming of the multibody passive-legged crawling vehicle (Stulce and Reinholtz, 1991).

3.1 Introduction

In contrast to most man-made vehicles, animals can generally cross rough terrain in an efficient and rapid fashion. It would be useful to have legged machines that could imitate the excellent mobility of animals. Hence, engineering researchers have studied animal locomotion to gain insights into the design of legged machines.

For this study, several caterpillar specimens were videotaped and analyzed in order to understand their principles of locomotion. Observations included the animal's geometry, gaits, leg trajectories, and workspace. The caterpillars exhibited an unexpectedly efficient gait and excellent rough terrain mobility.

These observations confirmed that most caterpillar motion could be emulated using a lengthwise chain of 6 DOF Stewart's Platform mechanisms that form the multibody passive-legged crawling vehicle. Additional insights from the caterpillar's locomotion are also directly applicable to the robot's physical structure and motion program. Such a robot would possess superb terrain adaptability.

3.1.1 Previous Studies of Animal Locomotion

A number of biologists and engineers have investigated animal locomotion, including Wilson (1966), Alexander (1990), McGhee (1985), Todd (1985), Fichter, et. al. (1987), Fichter and Fichter (1988), Donner (1987), and many others.

One of the primary reasons to study animal locomotion is to learn about gaits. A gait is a timing sequence for lifting legs and placing them on the ground. For example, horses choose to either walk, trot, canter, or gallop depending on their desire for speed, willingness to expend energy, and the terrain over which they are traveling.

Song and Waldron (1986) state the importance of gait studies as follows:

> ...it has become clear that gait is one of the major design factors in building a practical walking machine. Gait is the dominant factor in the design of vehicle geometry since it relates vehicle geometry to mobility. Moreover, the gait strongly affects the control algorithm...Gait also affects, to some degree, the energy efficiency of the machine.

The following terms are useful in describing and classifying gaits; they are taken from McGhee (1985):

"For an n-legged machine or animal, if every limb operates with the same cycle time, then the gait is said to be *periodic*."

A *regular* gait is one where all of the legs participate equally in propelling and supporting the body.

A gait is considered *symmetric* when the motion of a right-left pair of legs "is exactly half a cycle out of phase."

A gait can be thought of as a series of lifting and placing events. If no two events occur simultaneously then the gait is *non-singular*. However, if two or more events do occur simultaneously, then the gait is *singular*. These two definitions are useful when considering the combinatorial problem of determining the total number of theoretically possible gaits for an n-legged system. For example, McGhee (1985) has shown that for a quadruped there are 63,136 possible periodic gaits (including both singular and non-singular gaits).

McGhee mentions that many 4- and 6-legged animals use gaits that are mathematically proven to have optimum stability. These gaits are of the wave gait class.

Gait diagrams have been used by several researchers to graphically depict gaits. Figure 3.1 shows a gait diagram of a cockroach. The filled bars denote when a particular leg is in its support phase and the hollow bars indicate when the leg is in its transfer phase (i.e. lifted off the ground). Note that this gait is of the wave gait class; specifically, it is periodic, regular, symmetric, and singular.

Most previous walking machine projects have sought to create biped, quadruped, and hexapod vehicles using a single rigid body and actuated legs. This project aims to create a multibody passive-legged crawling vehicle where locomotion is caused primarily by movements of the body trunk. The natural analogues used in previous projects are humans, horses, and adult insects, whereas the natural analogue for the proposed vehicle is the caterpillar.

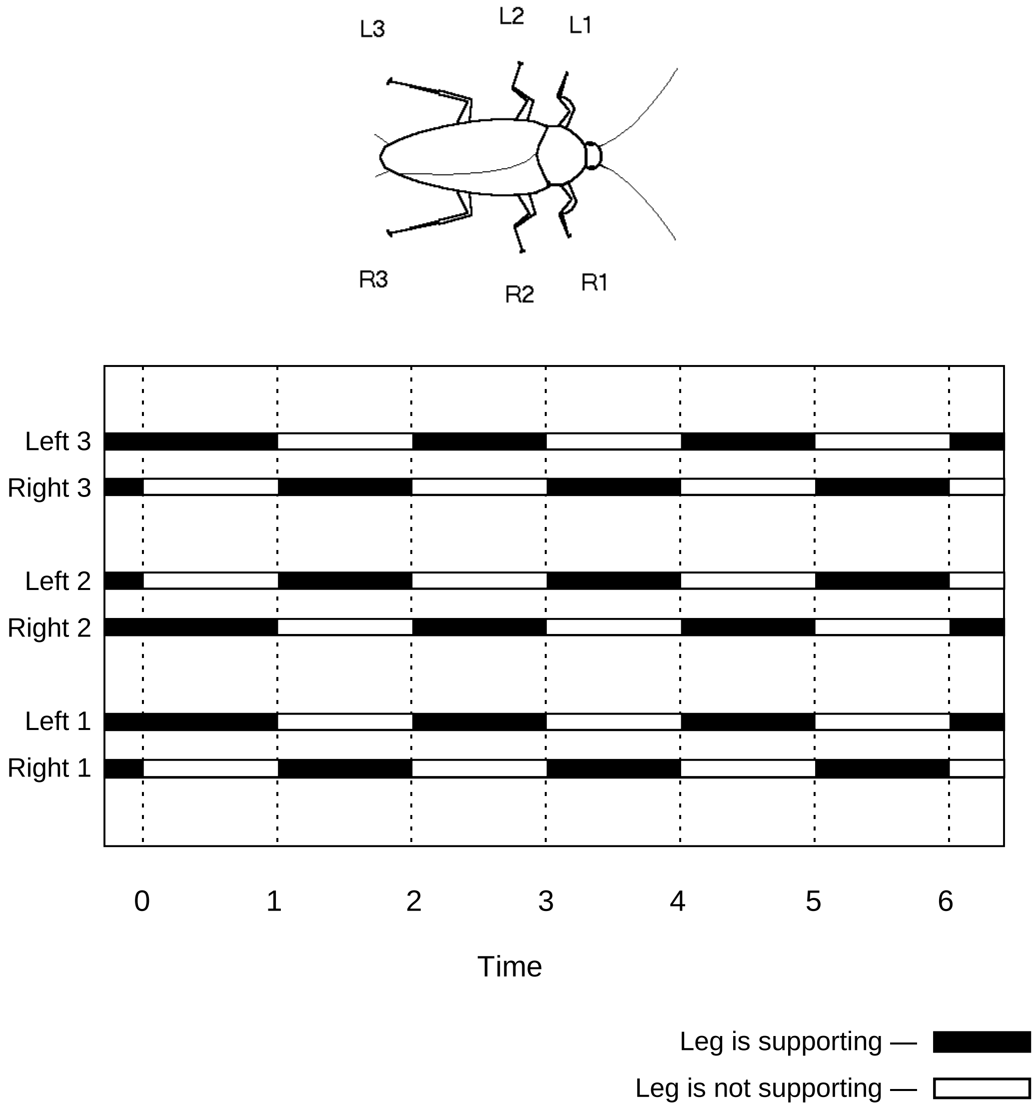

Figure 3.1 — Gait Diagram of a Cockroach's "Tripod Gait". (Adapted from Wilson, (1966).)

3.1.2 Caterpillars

Caterpillars are larvae of insects of the order *lepidoptera*, which, through an amazing process of metamorphosis, become adult butterflies and moths. Most caterpillars have twelve body segments, with eight of these segments having lateral pairs of short legs, (see Figs. 3.2, 3.3, and 3.4). Caterpillars have no wings, and are described by Dierl (1972), as having "no highly developed sense organs". Instead of the compound eyes found on many insects, they have six ocelli, which are "barely able to distinguish light from dark", on each side of their heads.

All caterpillars can make silken threads in varying amounts (Dierl, 1972). Their thread is extruded from a spinneret located just below their mouths. Many caterpillars can use their silk threads as bridges from one tree branch to another and to lower themselves to the ground.

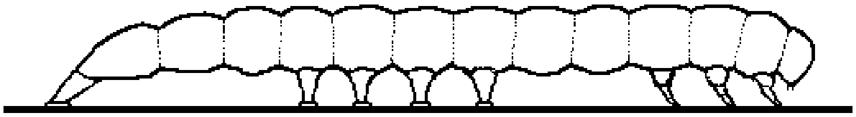

Figure 3.2 — Side View of a Standing Tent Caterpillar

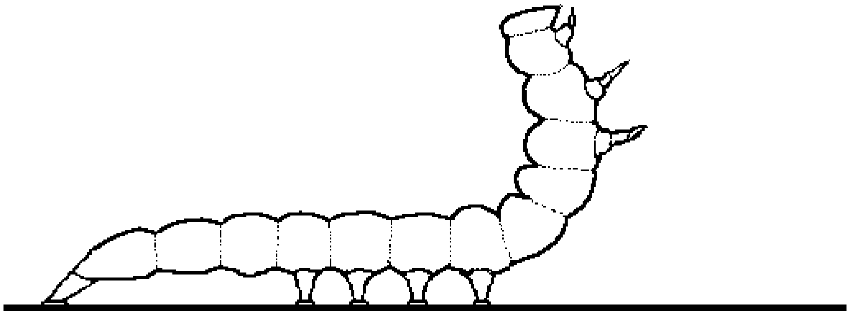

Figure 3.3 — Side View of a Pitching Tent Caterpillar

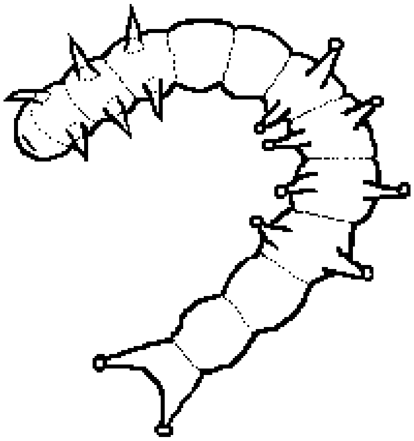

Figure 3.4 — Bottom View of Turning (Yawing) Tent Caterpillar

The body, or trunk, of caterpillars is soft and flexible. Special muscles lining the body wall exert pressure on the body fluids. As a result, the body is kept turgid, effectively creating a "hydrostatic skeleton" (Chapman, 1969).

Caterpillars have two different kinds of legs. The forward six legs, (the thoracic legs), each have a single leg segment and a claw (Dierl, 1972). The rear legs are referred to as prolegs. The prolegs are fleshy cylindrical protuberances from the body wall and have no segments, (or links). At the end of each proleg is a circle of curved hooks or "crochets" which are used for gripping the terrain. According to research described in Chapman (1969), each proleg has retractor muscles which are used for shortening the proleg when it moves during locomotion, for engaging and disengaging the crochets, and for creating a vacuum so that the proleg will function as a sucker on smooth surfaces.

Caterpillars move via a wave of muscular contractions that start at the posterior and progress forward to the anterior. During this motion, at least three segments are in varying states of contraction at the same time. The two feet on either side of each body segment move together, as a unit. It is believed that the muscle coordination is controlled primarily by a central nervous process modified by local reflexes (Chapman, 1969).

The back to front "wave" of motion mentioned above is common to almost all animals with appendages (Wilson, 1966). However, the in-phase motion of the lateral leg pairs is very unusual, because with most other animals, the two legs of each lateral pair move exactly a half cycle out of phase from each other (McGhee, 1985).

The caterpillar is especially interesting because of its ability to easily overcome obstacles that are large relative to its size, despite having very limited sense organs (Dierl, 1972).

3.2 Experimental Program

Several caterpillars were captured from the web, or "tent", which they had made in a cherry tree. By comparing the specimens with the description in Stehr (1987), it was determined that they were eastern tent caterpillars, (*Malacosoma americanum*). This species is considered to be a pest because they defoliate many fruit trees.

3.2.1 Videotaping Caterpillar Locomotion

The specimens were videotaped individually using a Super-VHS camera and recorder. Because of the caterpillar's small size, the video camera lens was used in the macro mode. The normal laboratory lighting, (a combination of fluorescent and natural light), was used. It was feared that using bright spotlights might change the animals' behavior, or that heat from the lights might harm them. Because of the moderate lighting conditions, the camera's depth of field was limited to approximately 8 cm.

Numerous problems resulted from the specimen's independent state of mind. To quote the Harvard Law, "Under the most rigorously controlled conditions of pressure, temperature, volume, humidity and other variables, the organism will do as it damn well pleases." (Bloch, 1982.) In the case of this experiment, the specimens usually crawled aimlessly around the table, tried to crawl onto the camera lens, attempted to escape, or refused to move at all. As a result, the animals would wander in and out of focus, or out of view altogether.

This problem was alleviated by using a rolled-up sheet of paper to create a pathway similar to the tree branches of the caterpillar's natural habitat. The caterpillars instinctively crawled along the edge of the paper, allowing the experimenter to hold the paper roll so that the caterpillar remained in focus. Also, as the animal crawled from one end of the paper to the other, the experimenter could translate the paper in the opposite direction so as to prevent the caterpillar from walking out of the stationary camera's field of view. Millimeter graph paper was used, allowing various length measurements to be made of the animals' bodies and locomotion when the videotape was replayed later in slow motion.

In addition to observations mentioned above, two steep "hills" were constructed from folded paper so that the caterpillar's obstacle crossing gaits could be observed. The specimens were also placed on plate glass and in glass beakers, and filmed from underneath, so as to get a bottom view of their locomotion.

Recording the videotape required approximately 10 hours to produce the resulting roughly 2 hours of tape. After the tape was finished, it was reviewed several times; critical sequences could be played in slow motion and frame-by-frame to allow careful observation. However, the slow time resolution of the camera, (30 interlaced frames per second), caused significant blurring to the images, particularly of the animals' feet as they moved.

3.2.2 Determination of Workspace

Measuring the caterpillar's workspace was one of the most important observations of this study, because workspace is the deciding factor that indicates whether a man-made robot can duplicate the motion of the caterpillar. Ideally, determining the workspace of a device is a simple matter of moving it to the limits of its range of motion and then measuring its angles and lengths. However, measuring the workspace of any invertebrate animal is complicated by the fact that their bodies behave in an elastomeric fashion. In the case of caterpillars, they are small enough that they can easily be squashed or torn apart by a researcher attempting to move them to their motion range limits.

By nudging the caterpillar with the fingers, or either moving or bending the paper the caterpillar was gripping, it was possible to maneuver the caterpillar's body into a number of different positions. It was presumed that the caterpillar would turn loose of the paper when it became uncomfortable with a particular body position. The most extreme position at which the caterpillar turned loose was considered to be its limit for that particular type of motion. This is an assumption that the body positions which are tolerable to the animal can also be reached via the animal's own muscular control, (i.e. in its workspace).

After recording, the videotape was reviewed to find the sequence where the specimen exhibited its most extreme movement. The tape was paused in freeze-frame mode at the caterpillar's most contorted moment, and its length and angular measurements were estimated. Typically, several of the caterpillar's segments would be doing the same type of motion, so that the gross motion of a group of segments could be measured; this result was then divided by the number of segments in the group to yield a per segment value. Determination of roll angles was helped by measuring off of the longitudinal stripe down the caterpillar's back. Similarly, pitch and yaw angles were gauged from the circumferential grooves located at the segment intersections.

3.3 Experimental Results

The caterpillars exhibited impressive locomotion capabilities. In general, their locomotion was statically stable (unlike mammals). The only exceptions were when they crawled up some vertical surfaces using their tiny crochets, and sometimes lost their grip and fell. After the falls, they used a statically unstable move to roll back over into a standing position. During the taping they demonstrated superior mobility even when they were not using their silk or claws.

3.3.1 Caterpillar Geometry and Workspace

Table 3.1 lists measurements taken from three nearly identical tent caterpillars. In general, the length measurements have an uncertainty of about 1 mm. Note that, because of the generally uncooperative nature of the specimens, repetitive tests were not made for several of the measurements.

3.3.2 Caterpillar Gaits

As discussed in the literature, caterpillars move by a wave of muscular contractions that proceed from the rear of the animal to its front. During each locomotion cycle, this "wave" is clearly visible as it travels up the caterpillar's body.

Table 3.1 — Approximate Physical and Locomotion Characteristics of Eastern Tent Caterpillars

Number of body segments	12
Number of legs	16 (8 pairs)
Mass	0.925 grams
Standing length	43 mm = L
Minimum length	33 mm = 0.76L
Maximum length	51 mm = 1.19L
Ratio of minimum to maximum length	0.65
Body diameter	4.5 mm
Maximum pitch per segment	80° (See Note 1 below.)
Maximum yaw per segment	53°
Maximum roll per segment	16°
Lateral leg pair spacing	5 mm (but can vary in order to grip)
Maximum observed speed	28.5 mm/sec using ≈ 2.5 waves (See Note 2 below.)
Ave. lengthwise spacing of adjacent prolegs	5.3 mm
Typical proleg step length	7.6 mm

Note 1: This may not have been voluntary. Also note that this is pitching up; negative pitch was not measured but is believed to be much smaller.

Note 2: After the experiments, when the caterpillars were released, they appeared to move much faster than this 'maximum'. Unfortunately, this was not documented on video and so their true top speed is unknown. The caterpillars' decision to finally demonstrate their speed capabilities may be attributable to their pleasure at finally being released from the jar, or more likely, the pavement was hot.

Unfortunately, whenever the 6 thoracic legs moved, they appeared blurry when the videotape was replayed. Thus, it was not possible to confirm whether the thoracic legs moved in the exact same manner as the prolegs. Often, it seemed that the caterpillars might be using their thoracic legs as feelers to perceive the terrain. Fortunately, the video images of the prolegs were clear enough to draw some conclusions. Therefore, the gait study concentrated on the caterpillars' prolegs. Also, since the prolegs have no segments (Dierl, 1972), they are similar to the legs on the proposed robot.

Unlike adult insects and most animals, the caterpillars' prolegs always move together, i.e. in phase.

Before taping, the author expected a single pair of legs to be in motion for each "wave", specifically, that just as leg pair i finished its swing and returned to the ground, the next leg pair, $i-1$, would lift off of the ground. However, the observations show that caterpillars rarely ever use this “single-leg-pair-per-wave” gait. Instead, they use a much more efficient “double-leg-pair-per-wave” gait, as illustrated in Fig. 3.5.

The top picture of Fig. 3.5 shows the caterpillar standing in its neutral stance an instant before it begins to move the prolegs on segment 12, (the anal claspers). Between $T=0$ and $T=3$, segments 12, 11, and 10 sequentially move forward by means of a wave of muscular contractions. At $T=3$ we see that segment 10 is compressed and the legs of segment 9 have tilted forward. At $T=4$, segment 9 has lifted its two legs off the ground and is at the middle of its swing forward. Simultaneously, segment 8 has begun to contract and tilt its legs forward in preparation for lifting. At $T=5$, segment 9 is shown just before it touches down. Meanwhile, segment 8 has lifted its legs and is now near the peak of its swing, and segment 7 is starting to contract and tilt its legs forward. An instant after $T=5$, the legs of segment 9 touch down and, **simultaneously**, the legs of segment 7 lift off the ground. The picture for $T = 6$ is just like $T = 5$, except that the "wave" has moved forward another segment so that it is now centered over segment 7. After $T = 6$, the remaining prolegs move in a similar fashion, and the wave continues to move forward along the caterpillar's body until segment 1 completes its move.

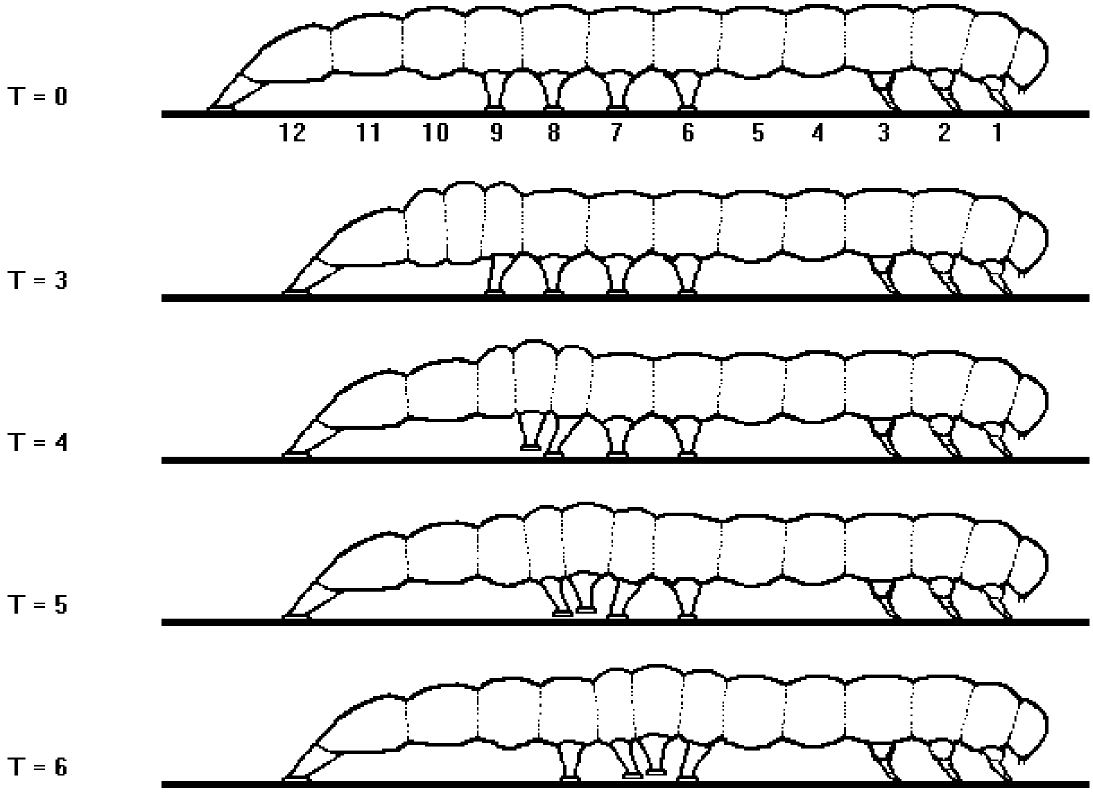

Figure 3.5 — Locomotion Sequence of a Tent Caterpillar

(Note that the segment numbering scheme used here is different than that used in entomology literature.)

Thus, the general pattern is as follows: just as leg pair i touches down, leg pair $i-2$ takes-off. It appeared that each segment began moving when the previous segment was half finished with its step. The proleg portion of this gait is graphically depicted in Fig. 3.6.

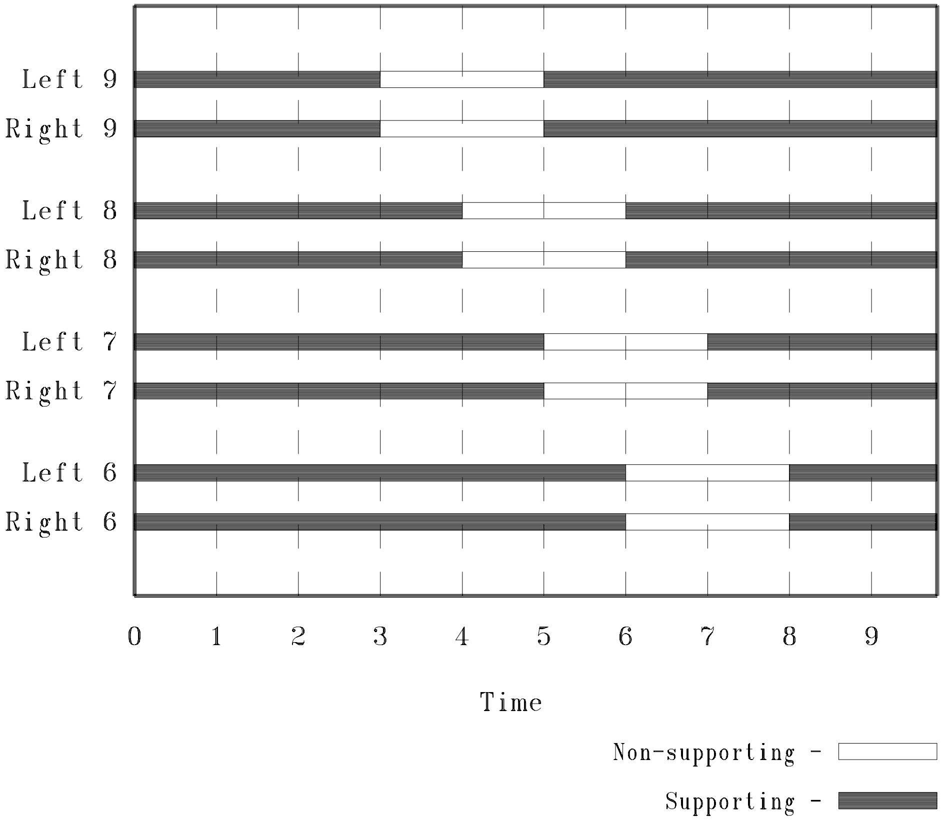

Figure 3.6 — Tent Caterpillar Gait Diagram

Applying the terminology given in McGhee's work to this animal results in some difficulties, since the definitions were apparently not made with caterpillars in mind. Strict adherence to the definitions would cause unnecessary confusion by labeling the caterpillar's right-left leg pair motions as "non-symmetric" because their movements are exactly in-phase rather than out of phase. Thus, it is desirable to refine the definitions slightly by stating that lateral legs that move 180° out of phase are exhibiting "opposite phase symmetry", and lateral legs that move together are demonstrating "in-phase symmetry". Relative phase angles other than 0° and 180° are termed "non-symmetric". (An example of a true non-symmetric gait is a horse's gallop.) Figures 3.1 and 3.6 clearly contrast the cockroach's opposite-phase symmetry with the caterpillar's in-phase symmetry.

Using this slightly modified version of the classification terminology given in the reference by McGhee (1985), it can be said that the caterpillars achieved locomotion by using periodic, singular, regular, in-phase symmetric, wave gaits.

Caterpillars can continuously vary the frequency of their locomotion cycle in order to achieve different speeds. During higher speed motion, several specimens were observed with roughly 2.5 separate "waves" of foot motion travelling along their trunks simultaneously. In one instance, when a caterpillar was pushed from the front, it backed-up using a reversed gait in which the wave of contractions simply traveled from the front of its body to the rear.

3.3.2.1 Rough Terrain

When standing on or crossing over uneven terrain, the caterpillar's body posture conformed to the terrain in a smoothed manner. That is, it did not conform to every small irregularity, but it did assume the general shape of the terrain. No attempt was made to keep the legs aligned in a vertical direction; instead, as the caterpillar's body adapted to the underlying terrain, its legs were kept perpendicular to the centerline of the caterpillar's body trunk. This resulted in each leg being normal to a smoothed approximation of the local ground surface on which its foot rested. When standing on rough terrain, the caterpillar generally maintained its longitudinal leg spacing at roughly equal arc lengths along its curving body.

The caterpillars crossed most hills and trenches using the terrain conforming manner described above. Indeed, hill-type obstacles barely slowed the caterpillars down. The video-still in Fig. 3.7 shows a caterpillar climbing a tall obstacle relative to its own size, consisting of the author’s index and middle fingers. Moments later the caterpillar had moved its center of mass to the top of the “hill”.

Figure 3.7 — Eastern Tent Caterpillar Climbing a Large "Hill"

3.3.2.2 *Crossing Large Obstacles*

Since caterpillars have 16 legs, they can remain statically stable without having all of their feet on the ground. The caterpillars use this to good advantage when they encounter large terrain features with abrupt changes in curvature. The caterpillars used a cantilever maneuver similar to that shown in Fig. 3.3 to "bridge" across abrupt gaps in the terrain. Interestingly, once a caterpillar had bridged a gap and found footholds for its front legs, it resumed the same gait as before! That is, the gait was still a periodic, in-phase symmetric, singular wave gait. Although the segments directly over the void were out of contact with the ground, they nevertheless moved forward at the appropriate time during each locomotion cycle. To the observer, it appeared that the caterpillar was "pumping" its mass from one base of support to another.

3.3.2.3 Recovering After a Fall

Occasionally, when a caterpillar was climbing up a vertical paper surface, it lost its grip and fell, ending up on its back. After bouncing on impact, the caterpillar would roll over, right itself, and then be on its way again.

Interestingly, the righting maneuver was not statically stable. Specifically, if a caterpillar finds itself lying on its back, it raises several segments from both the front and rear of its body upward and slightly to one side. This effectively moves the caterpillar's center of gravity beyond the support base of its rounded back. Since this is an unstable position, gravity causes the upraised body segments to fall, causing the body to roll off of its back onto its side. Once on its side, the caterpillar rolls 90° onto its feet again. This roll maneuver begins at segments 1 and 12. The rotating action proceeds from the two ends towards the center of the caterpillar until all of the segments have rolled back onto their feet. Hence, the instability turns out to be beneficial in this case.

3.3.3 Leg Pair Trajectories

Notice in Table 3.1 that the caterpillar's average lengthwise spacing between adjacent prolegs is 5.3 mm. If only one segment moved at a time, we would expect each segment's stride to be 2 or 3 mm long because the segments have an average minimum to maximum length ratio of 0.65. However, Table 3.1 also lists the typical proleg step length to be 7.6 mm, actually beyond the initial position of the next leg pair.

This extra-large stride is brought about, partially, by the double-leg-pair-per-wave gait. It also results from the caterpillars' use of leg trajectories that incorporate pitching or tilting of the leg pairs to effectively swing the legs. Notice in Fig. 3.5 that just before a segment's legs lift off of the ground, the segment begins to tilt forward. During its swing phase, the leg pair straightens to a vertical orientation. Then, at the end of its stroke, the leg pair tilts backward as it returns to the ground. This pitching motion allows longer, more efficient steps, allowing each segment more time to accelerate and decelerate. Thus, a given speed can be produced using weaker muscles.

The proleg retraction during locomotion mentioned in the Chapman (1969) reference could not be confirmed in this study because the video images of the legs were blurred. However, if the prolegs were retracting during locomotion, they were not retracting very far. It was clear that when a segment was at the peak of its motion, it was approximately 1 mm above the rest of the caterpillar (notice how segment 9 “humps” at $T = 4$ in Fig. 3.5). It may be that this vertical distance is sufficient for the prolegs to swing without retracting.

3.4 Application to Robot Design

Since the caterpillar's locomotion results mainly from body-trunk movements, and because its unjointed prolegs are essentially passive, the caterpillar is an appropriate biological analog of the multibody passive-legged crawling vehicle. As such, it provides excellent examples of the potential of such a vehicle, and gives insights into the design and motion programming of its mechanical counterpart.

3.4.1 Legs

From the observations of the caterpillar's proleg segments, it is concluded that the proposed vehicle can emulate most of the caterpillar's mobility without the use of actuated legs. It appears that simple legs rigidly attached to the payload boxes would be effective; however, this does not rule out the possibility of adding passive (non-actuated) freedoms to the legs to enhance terrain adaptability, shock absorption, and/or energy storage.

3.4.2 Actuation Units

During the early stages of the crawling vehicle conceptual design, the double octahedral VGT was considered as a possible candidate for use in the actuation units (see Fig. 2.4). However, after the caterpillar observations, it became obvious that the double octahedral VGT simply did not have the necessary mobility to emulate the caterpillar's locomotion. In particular, it lacked the necessary torsional mobility about its longitudinal axis and it was completely inadequate for the task of having two actuation units cooperatively control the position of their connecting leg pair.

Tests performed using a computer model developed by the author and a scale physical model constructed by Paul Mele (1991) indicate that a Stewart Platform mechanism can be made with a workspace very similar to that of one body segment of a caterpillar. Therefore, it can be concluded that it is kinematically feasible to emulate the caterpillar's excellent mobility using the proposed design.

3.4.3 Linear Actuators

As shown in Table 3.1, the ratio of the caterpillars' minimum to maximum length is 0.65. This is encouraging because simple, 2-section telescoping linear actuators can also have this range of motion. Thus, the Stewart Platforms can use simple linear actuators rather than having to use more complicated compound linear actuators, (see Fig. 3.8).

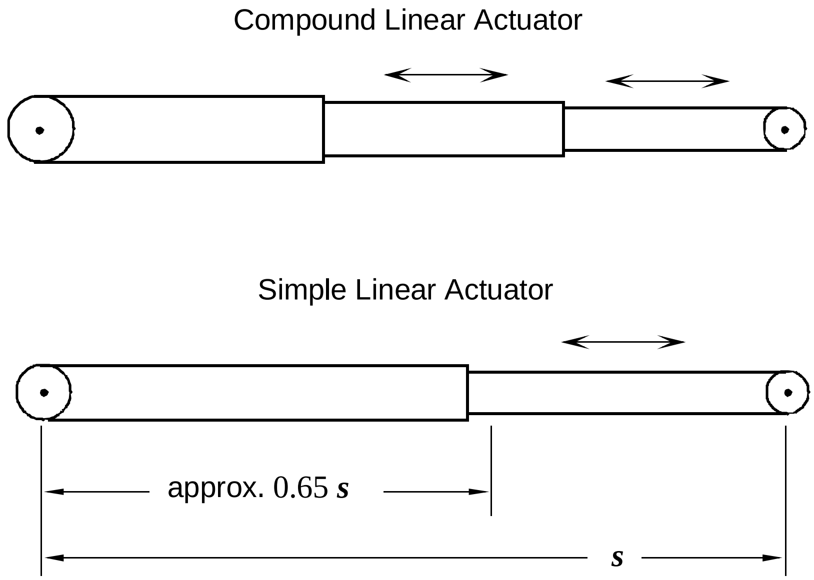

Figure 3.8 — Comparison of Compound Linear Actuator and Simple Linear Actuator

3.4.4 Motion Programming

Because the actuation units can have workspaces similar to a caterpillar body segment, it is possible to program a crawling vehicle to imitate the gaits and leg pair trajectories that the caterpillars were observed to use.

It was surprising that the caterpillars' double-leg-pair-per-wave gait and their tilting leg pair trajectories were used in all situations, including obstacle crossing. The caterpillars had longer, smoother strides than expected. So the question arises, “Will programming a multibody passive-legged crawling vehicle to imitate the caterpillar's ‘motion program’ actually be beneficial?” Answering this question will be an important test case for the simulation tools. In fact, the simulation will be expressly designed with this question in mind.

3.4.5 Payload Boxes

From the discussion in Section 3.3.2.3 on recovering after a fall, it is apparent that the caterpillar's cylindrical body is very useful. To enable the proposed robot to perform this maneuver, it is necessary to change the conceptual design. Specifically, the payload boxes should be changed to be rounded on top, (see Fig. 3.9). A cylindrical shape would also be more efficient from the point of view of volume per surface area and payload volume per vehicle mass.

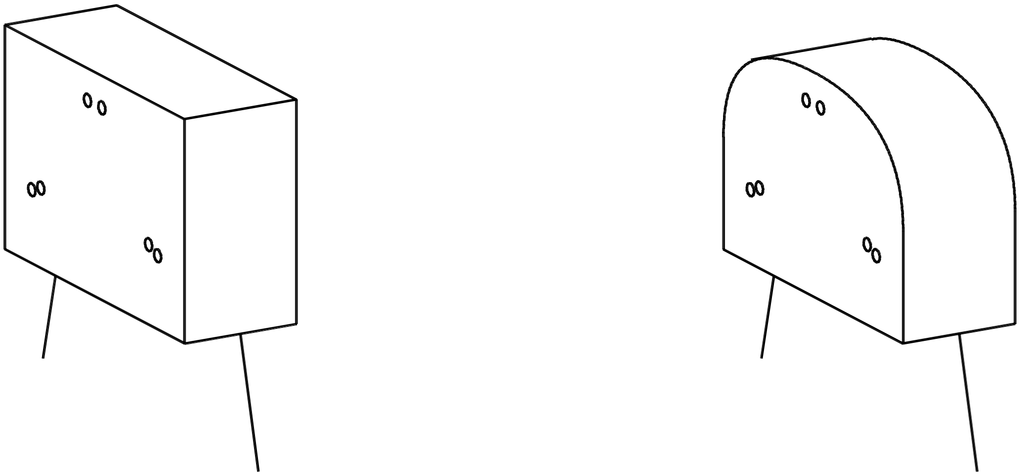

Figure 3.9 — Rounded Top Payload Boxes

Figure 3.10 shows a computer rendering that illustrates a complete crawling vehicle with this change implemented.

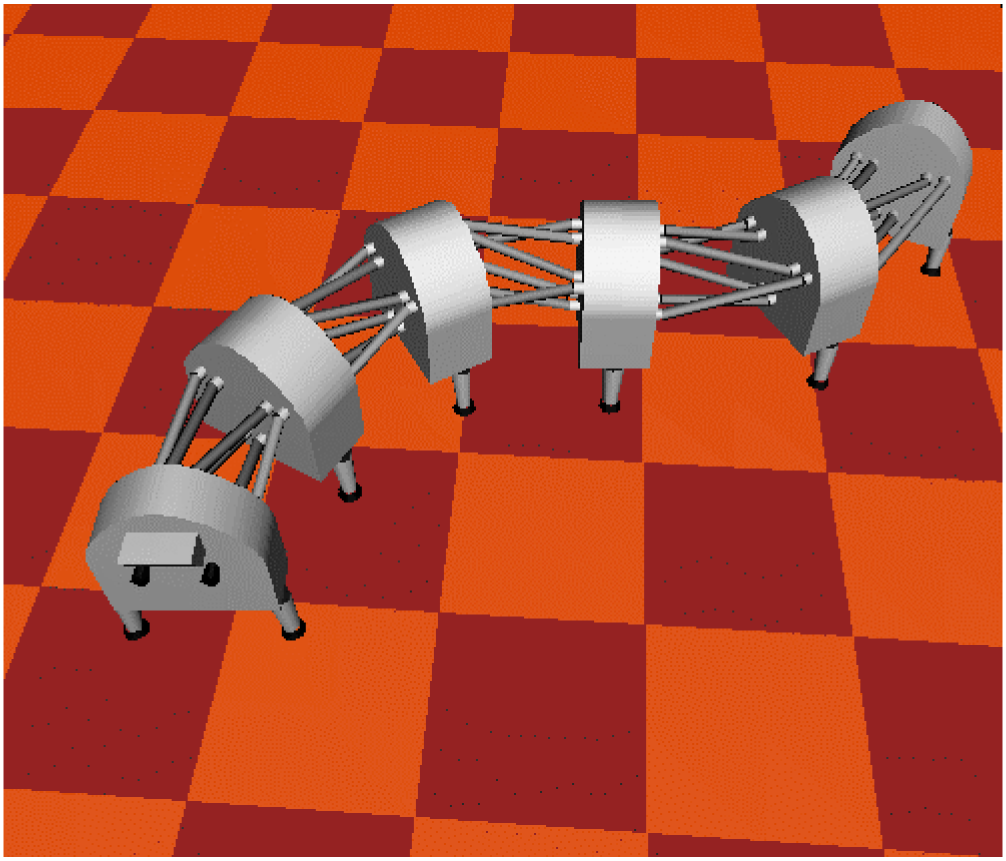

Figure 3.10 — A Crawling Vehicle Using Payload Boxes with Rounded Tops

3.5 Chapter Summary

The caterpillar observations reported in this chapter include measurements of its geometry, range of motion, gaits, and leg trajectories. These observations confirm that the caterpillar is indeed a suitable biological counterpart for the multibody passive-legged crawling vehicle. The caterpillar observations have had a direct effect on the design of the actuators, actuation units, legs, payload boxes, and motion program of the vehicle.

Most notably, the caterpillars' gait is surprisingly efficient and versatile; the same basic gait is used for almost all locomotion, including obstacle crossing. Since the preliminary mechanical design of the crawling vehicle has been shown to have a range of motion similar to that of the caterpillars, it is kinematically feasible to imitate the caterpillar gaits and leg step trajectories with the crawling vehicle. This idea will be pursued and tested in subsequent chapters as we develop the motion programming algorithms and computer simulation techniques that will be used as tools in the configuration design stage of the multibody passive-legged crawling vehicle. But first we must lay the groundwork in the next chapter — Modeling.