*Even the longest journey begins with the first step.*

*— Ancient Chinese proverb*

# 1. Introduction and Literature Review

This research concerns a unique class of mobile robotic vehicle called the "multibody passive-legged crawling vehicle". This class of vehicle has the potential of having better rough terrain mobility than any previous type of man-made land vehicle.

## *1.1 The All-Terrain Mobility Problem*

Mankind has long sought improved methods of land transport. Over the centuries, these land locomotion methods have included traveling on foot, riding on the backs of horses or other animals, using carts and wagons drawn by both humans and animals, and using a variety of vehicles powered by steam, internal combustion, or other engines. With the advent of automation and robots in the 20th century, a new level of sophistication has been added to these methods, namely, the development of automated vehicles, or mobile robots, which can be sent to perform these tasks with little or no human intervention.

In recent years, practical mobile robots have been successfully used in controlled environments such as factories, offices, and hospitals, as well as outdoors on prepared surfaces and terrain with minor irregularities. However, thus far, the operation of mobile robots in extremely rough, uneven terrain has been impossible or unreliable at best. Nevertheless, many benefits would result if robotic mobility "in the field" were made practical (Whittaker, 1993). Hence, the study of "field robotics" has become an active area of research.

## *1.2 Research Approach*

Several previous publications, including papers by McGhee (1985), Fichter, Fichter and Albright (1987), Bares and Whittaker (1989), and Oral (1994a) have noted that approximately 50% of the Earth's land surface is inaccessible to wheeled or tracked vehicles, but that, in contrast, most animals can cross rough terrain in an efficient and fairly rapid fashion. Thus, it is desirable to create legged machines that will imitate the excellent mobility of animals.

Researchers have therefore looked to the animal world for inspiration, attempting to develop walking vehicles to imitate the body structure and methods of locomotion of mammals, adult insects, human beings, and other arthropods (life forms with jointed legs). However, reliable mobility on extremely uneven terrain remains an elusive goal for man-made devices.

Technological challenges abound in almost all aspects of mobile robot research. However, the most critical factor that impedes creating legged vehicles that can safely operate on rough, uneven terrain has been the need for the robot to reliably detect and reach enough secure footholds. If the legs of a walking vehicle are unable to reach a sufficient number of safe footholds, the robot will be unstable and will fall over, possibly damaging itself. Exacerbating the problem are foothold areas that appear safe to the sensors of the robot, yet, because of hidden holes, loose rocks, or soft soil, fail to support the weight of the vehicle when it places a leg in those locations. This problem is symptomatic of the underlying inadequacies in terrain sensing and controls, and the lack of a safety factor in the form of redundant supporting legs. State-of-the-art sensing and controls technology still cannot duplicate the abilities of most arthropodic animals.

Therefore, rather than trying to run or walk like “higher” life forms, this research seeks to solve the all-terrain mobility problem by emulating the crawling locomotion of a comparatively simple life form—a baby insect. Specifically, the biological counterpart for the vehicle concept described in this research is the caterpillar, the larva of a moth or butterfly. Caterpillars have flexible, longitudinally segmented bodies with 16 stubby legs. They move via waves of muscular contractions that start at the posterior and progress forward to the anterior. Caterpillars are nearly blind and presumably have very little intelligence, *yet they exhibit superb all-terrain mobility* relative to their size.

Therefore, the approach taken in this research was to advance the development of a new category of vehicle that would be able to crawl over difficult, uneven terrain in a manner similar to caterpillars. To achieve this aim, the design choices for the crawling vehicle were guided by the hypothesis that the robot would achieve caterpillar-like mobility if its body structure and methods of locomotion could be made to emulate those of the caterpillar. As will be shown later in this work, this hypothesis is true.

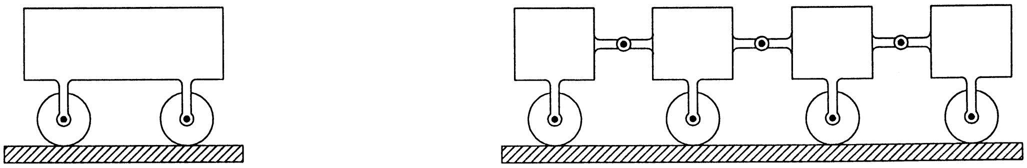
## 1.3 Classification of Vehicles

To date, virtually all legged vehicle research has concentrated on emulating the locomotion of animals by creating machines with a single rigid body and articulated legs or limbs. The following introductory sentence, taken from a paper on insect walking by Wilson (1966), leads us to consider another possible means of locomotion.

> The mechanics of various types of animal locomotion fall into two major categories: locomotion involving appendages and locomotion involving only movements of the trunk.

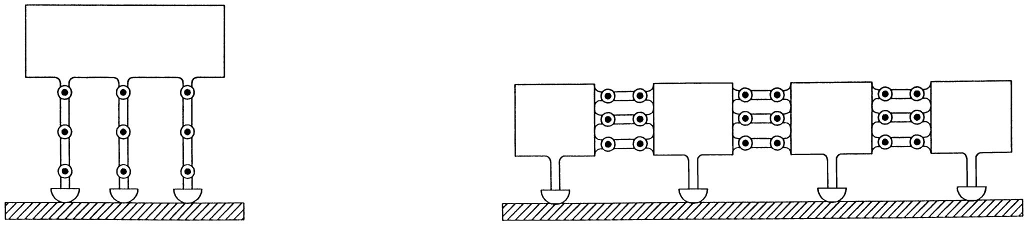
Devices based on the first category will hereafter be referred to as "walking" vehicles and devices based on the second category as "crawling" vehicles.

Most types of animal and legged machine locomotion fall into one of the two categories described above. Further distinctions can be made when describing the locomotion of man-made land vehicles in general. The classifications are enumerated in Fig. 1.1.



(a) Single-body Wheeled Vehicle

(b) Multibody Wheeled Vehicle



(c) Single-body Legged Vehicle

(d) Multibody Legged Vehicle

**Figure 1.1 — Types of Land Vehicles**

The most common type of vehicle, shown in Fig. 1.1a, has a rigid body and is driven on wheels or tracks, such as an automobile, a bicycle or a bulldozer. Trains and trolleys are examples of multibody vehicles that run on wheels or tracks, as indicated in Fig. 1.1b. Most legged vehicles have been based on the concept of a single rigid body having articulated legs, which is illustrated in Fig. 1.1c. Finally, Fig. 1.1d shows a multibody legged vehicle. Such a vehicle can produce controlled relative motion of its multiple bodies. It could have legs with active, actuated joints, or it could have passive, non-actuated legs. The crawling vehicle presented in this dissertation belongs to this final class.

## 1.4 The Advantages of Legged Vehicles on Rough Terrain

Wheeled vehicles excel when used on prepared surfaces, such as roads and railways. They are cost-effective, efficient, and capable of achieving higher velocities than any legged vehicles or animals. Enhancements to wheeled vehicles, such as track-laying apparatus and innovative suspensions like the rocker-bogies used on the Sojourner and the Rocky series of robots (Gat et. al., 1994 and Bickler, 1998), have extended the rough terrain mobility of wheeled vehicles considerably. However, as the terrain becomes increasingly difficult, a point comes where wheeled vehicles prove inferior to legged vehicles.

Oral (1994a) states that paddy fields, sandy soils, and undulating terrain are troublesome for wheeled vehicles to cross; and specifically, that traveling over undulating natural terrains involves difficult tasks for wheeled vehicles, such as step climbing, gap crossing, gradients, side slopes, and water crossing.

Similarly, traversing many man-made “terrains” is also difficult for wheeled vehicles because of narrow doorways, narrow hallways, sharp turns, floor irregularities, ramps, steps, staircases, and ladders.

Several researchers have described the inferiority of wheels from the soil mechanics viewpoint. McGhee (1985) and Oral (1994a) write that, when traversing soft soils, wheels sink down and must effectively be continuously climbing out of a hole and/or expending energy to compact the soil (see Fig. 1.2). According to Bekker (1956), “A wheel driven in a soft terrain may not be as economical as walking or running: it requires more power per unit of weight”. Todd (1985) writes that the foot’s “most fundamental advantage over the wheel” is that the compaction resistance of the soil can contribute to its forward thrust, whereas in the case of a wheel, compaction resistance reduces the forward thrust.

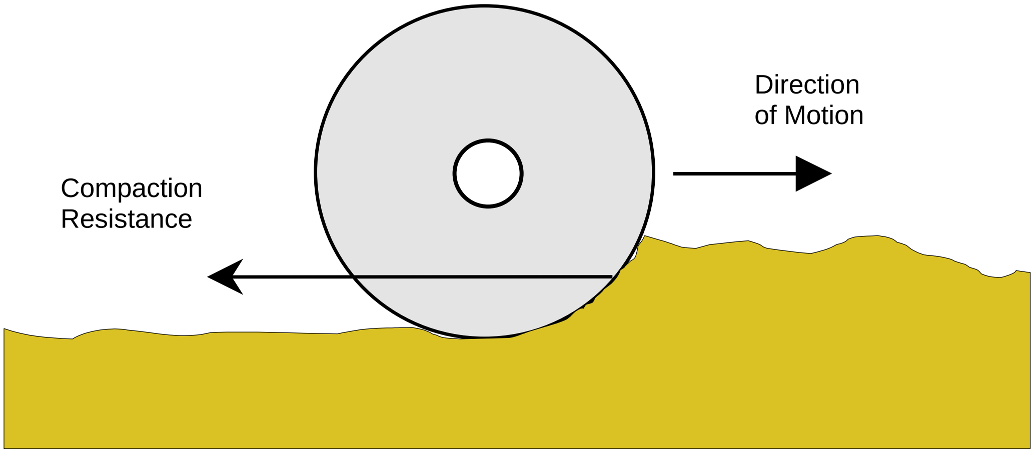


**Figure 1.2 — Compaction Resistance of a Wheel in Soft Soil
(After Bekker (1956) and Todd (1985))**

Song and Waldron (1989) list five potential advantages of legged vehicles over wheeled or tracked vehicles when moving over rough terrain:

1. Higher speed.
2. Better fuel economy.
3. Greater mobility. [This includes the ability to step over obstacles and travel across terrain that is impossible for wheeled and tracked vehicles.]

4. Better isolation from terrain irregularities. [This enables a smoother ride.]
5. Less environmental damage. [Wheeled and tracked vehicles leave continuous ruts in soft soils, whereas legged vehicles leave only discrete footprints.]

In general, legged vehicles become attractive for any application requiring traversal of terrain that is too difficult for wheeled and tracked vehicles, and is too expensive or dangerous for humans. In his excellent introduction to walking machines, D. J. Todd (1985) lists a number of possible applications that are suitable for legged vehicles. Among them are:

1. planetary exploration,
2. nuclear maintenance,
3. military transport,
4. mining,
5. hazardous material handling,
6. construction and related activities,
7. agriculture and forestry,
8. rescue and firefighting,
9. the study of locomotion (zoology and engineering),
10. orthotic and prosthetic aids,
11. artificial intelligence research,
12. education, art, and entertainment.

The crawling vehicle proposed in this research could be adapted for all of the applications listed above.

## *1.5 The Advantages of Multibody Vehicles on Rough Terrain*

Bekker (1969) describes four main types of locomotion failures for wheeled vehicles attempting to cross rough terrain: clearance failures, vibration failures, traction failures, and stability failures. Clearance failure modes include hang-up failures, “when the bottom of the vehicle interferes with the obstacle”, and nose-in failures, “when the front end [or rear end if going in reverse] of the vehicle interferes with the obstacle”. Vibration failures result from excessive bouncing and vibrations that reduce the controllability or ride comfort of a vehicle below a tolerable level. Traction failures are caused by the slipperiness or looseness of the ground. Finally, stability failures occur when transverse or longitudinal slopes cause a vehicle to overturn. While Bekker was considering wheeled vehicles in the above description of failure modes, the same discussion generally applies to legged vehicles as well.

Multibody vehicles, both wheeled and legged, have several advantages over their single-body counterparts when operating on rough terrain. First, the flexibility provided by their multiple bodies allows them to avoid many clearance failures to which rigid-body vehicles are prone. Furthermore, by proper control of their various bodies, multibody vehicles can select where they contact the ground, thus reducing their vulnerability to traction failures. Finally, for the same size ground contacting members (be they wheels or legs), multibody vehicles provide greater effective workspaces, enabling them to reach safe support areas on more extreme, uneven terrain, thus reducing the possibility of stability failures. Also, because their multibody structure allows them to conform more closely to undulating terrain, multibody vehicles can maintain a lower center of gravity than their rigid body counterparts, once again making them less vulnerable to stability failures.

## 1.6 Stability—The Key to Rough Terrain Mobility

Rough terrain mobility is the ability of a vehicle to traverse uneven terrain without having to halt in order to avoid an eminent locomotion failure and without being halted by a locomotion failure that has actually occurred. Section 1.5 presented the four modes of locomotion failure for wheeled vehicles on rough terrain as defined by Bekker (1969). These failure modes also apply to legged vehicles, but with a different distribution of risk. Specifically, with wheeled vehicles operating on rough terrain, the ground clearance concerns of avoiding hang-up failures and nose-in failures are generally the most critical because of the relatively limited workspace of most wheel suspensions. In contrast, with legged vehicles, the most common limiting failure mode is not clearance, since their leg mechanisms usually have relatively large workspaces; instead, the most critical concern for legged vehicles is the stability failure mode. Thus, the most important enabling factor that determines the rough terrain mobility of a legged vehicle is its ability to remain stable and avoid tipping over or falling down when it confronts difficult physical obstacles.

### 1.6.1 Defining Stability

The stability of a vehicle can take several forms. Because of its importance to locomotion, it is worthwhile to consider the subject of stability in greater detail. The stability of a vehicle can be defined as both a state, the *instantaneous stability*, and more broadly, as an overall performance goal for a period of time, the *effective stability*.

The *instantaneous stability* state of a vehicle indicates, at a particular instant in time, whether the vehicle is safely supported on the ground or is in the act of ballistic flight or falling. The instantaneous stability is determined by the relationship between the sum of the forces and moments acting on the vehicle and the positions of its load-bearing feet. Specifically, at any point in time, the feet on the ground that support the vehicle define the base of support or area of support for the vehicle. A vehicle is instantaneously stable when the line of action of the vector sum of the gravitational and inertial forces passes through the vehicle's area of support. This is illustrated in Fig. 1.3, where a legged robot is shown supported by three of its legs as it operates on a slope. In this example, the sum of the inertial forces is relatively small and its footholds are positioned with respect to the center of gravity so that the robot is stable at that point in time.

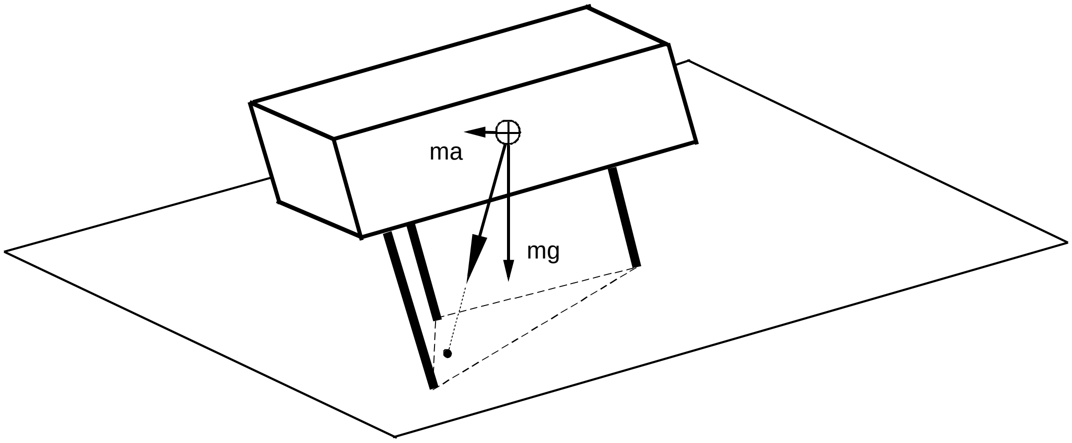


**Figure 1.3 — Example of an Instantaneously *Stable* Vehicle**

In contrast, a vehicle is instantaneously *un*stable, and thus either falling or in a ballistic flight trajectory, when the “the resultant vector of the gravitational and inertial forces meets the ground outside the base of support“ (Todd, 1985). This situation is illustrated in Fig. 1.4 for a legged vehicle on level terrain. In this case, because the line of action of the resultant vector lies outside the support area of the vehicle, the vehicle will tip over, rotating about an axis that passes through the locations of the two leftmost feet. The example shows that large inertial forces, such as those that occur during sudden decelerations, can destabilize a vehicle that would have otherwise been stable if the gravitational force had been the only consideration.

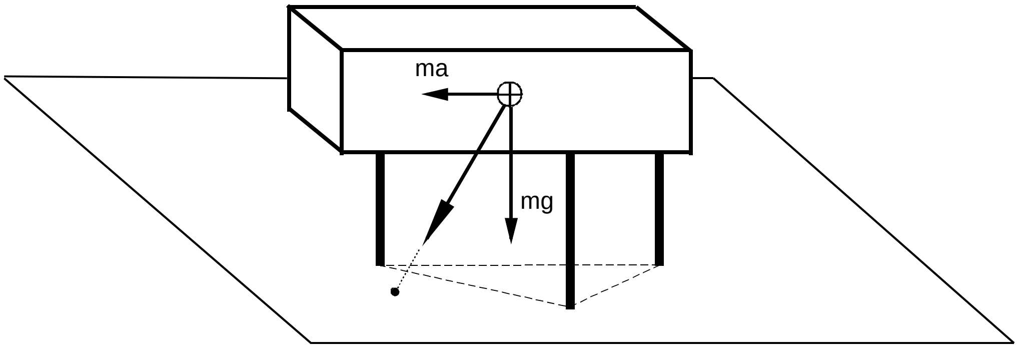


**Figure 1.4 — Example of an Instantaneously *Unstable* Vehicle**
**(After Todd (1985))**

Note that, although these example figures show legged robots, this definition of instantaneous stability also applies to wheeled vehicles, with the only difference being that the support members are wheels rather than feet.

The *effective stability* of a vehicle is a critical performance issue. It is the resultant of the total vehicle-terrain system, including the influence of the entire locomotion control system (i.e. terrain sensing, path planning, body attitude sensing, actuator outputs, etc.); therefore, it is difficult to define mathematically. However, simply stated, a vehicle is effectively stable if it never "loses control" and accidentally hits the ground, and it is effectively *un*stable if it ever does.

More precisely, a vehicle is stable, in the effective sense, so long as it does not fall in an unrecoverable manner. Consequently, whenever it contacts the ground, it does so using its intended ground contact members (typically its feet or wheels) rather than other parts of its structure (i.e. its side, back, etc.). Conversely, a vehicle is unstable, in the effective sense, when it begins to fall in a manner that is *unrecoverable*, so that, despite the best control reactions of the system, it nevertheless will contact the ground with portions of its structure *other* than those designed for terrain contact. (This implies that a vehicle can remain effectively stable even though it undergoes instantaneously unstable states and begins to fall, so long as the control system of the vehicle enables it to recover from the fall before hitting the ground.)

Maintaining effective stability is crucial to the operation of a mobile robot because falls can often damage the robot and cripple its performance. Even if a robot survives a fall unscathed, it must still have the ability to right itself and get back on its feet to avoid needing outside intervention to rescue the vehicle. In the case of some long-range exploration missions, the alternatives are self-recovery or total mission failure. Even when survivable, the act of falling and getting up again slows the locomotion progress of the vehicle.

There are two main approaches used for preserving effective stability. One method is to continuously maintain instantaneous stability at all times during locomotion. The other is to allow instantaneously unstable states, but to recover from these states before actually hitting the ground by use of a control system that takes into account the dynamics of the system.

Based upon these two general approaches, a vehicle can maintain effective stability through four basic operating modes: static stability, quasi-static stability, quasi-dynamic stability, and dynamic stability. Note that the definitions of the stability modes that follow are generic in that they can apply to both wheeled and legged vehicles.

### 1.6.2 Static Stability

Statically stable locomotion is based on the approach of continuously maintaining instantaneous stability. It is referred to as “statically” stable because the inertial forces acting on the robot are assumed to be negligible, thus reducing the evaluation of the instantaneous stability to a statics problem concerning the relative positions of the vehicle center of gravity and its supporting members. Stability is thus achieved by maintaining an area of support beneath the center of gravity at all times. Vehicles that have actuated support members (e.g. legs) must carefully plan the sequence of motion for these members (e.g. the gait) so as to ensure the continuity of its base of support during locomotion. Statically stable locomotion usually requires having at least 3 support members on the ground at a time (except sometimes for vehicles with feet or wheels having very large ground contact areas). A legged vehicle generally requires a minimum of 4 legs to move in a statically stable manner, so that one leg can move while the other three legs provide support. Note that vehicles operating in static stability mode must limit their speeds to ensure that accelerations, and hence inertial forces, are insignificant relative to the gravitational force acting on the vehicle.

### 1.6.3 Quasi-Static Stability

Quasi-statically stable locomotion is also based on the approach of continuously maintaining instantaneous stability. However, it differs from static stability in that it takes into account inertial forces. Specifically, instantaneous stability is not evaluated in abbreviated form, as with static stability, but is determined using the vector sum of the gravitational *and* inertial forces acting on the vehicle. Then, during locomotion, the motions of the supporting members of robot are planned carefully so that an area of support is always maintained where the line of action of the net force vector meets the ground. As with static stability, the continuous maintenance of stability generally requires 3 supporting members (4 for legged vehicles so that one leg can move).

### 1.6.4 Quasi-Dynamic Stability

Quasi-dynamically stable locomotion is based on the approach of intermittently entering into and recovering from states of instantaneous instability. Todd (1985) described this it as “alternating balance stability”. This locomotion involves dynamic transfers from one stable base of support to another. That is, starting from an instantaneously stable position, the robot either jumps over to, or falls onto, a new instantaneously stable position.

For example, a 4-wheeled vehicle moving rapidly over rough terrain may bounce around and temporarily ride on just 2 of its wheels. But so long as this destabilization doesn't flip it over onto its side, it will fall back down onto all 4 wheels again, thus regaining stability without active control. Raibert (1986) and Todd (1985) both describe the work of Kato and his colleagues, in which a biped robot used a quasi-dynamic stability mode to walk. Specifically, each foot of the robot was large enough to support the robot in a statically stable manner. To walk, the robot stood on one foot and then moved its “catching” foot into position ahead of the supporting foot. Then, once per locomotion cycle, the machine tipped forward and fell onto the catching foot, which then became the supporting foot, and the cycle repeated. Thus, in certain cases, a dynamically moving vehicle may not need to perform any active response to remain effectively stable.

### 1.6.5 Dynamic Stability

Dynamically stable locomotion is based on the approach of recovering from nearly continuous states of instantaneous instability. Because of the methods it employs to maintain effective stability, this mode of operation has also been referred to as “active balance” and “dynamic balance” (Raibert, 1986). The locomotion cycles of dynamically stable vehicles include instabilities of two basic types: falling motions like that of an inverted pendulum (when one or more support members in contact with the ground act as pivots) and ballistic flight (when no supports are in contact with the ground).

In the case of inverted pendulum instability, the robot can maintain its effective stability by several methods. One method of recovering involves quickly moving so as to alter its shape (i.e. changing its posture or the positions of its limbs) in order to shift its center of gravity relative to its supporting members. Alternatively, it can move parts of its structure (i.e. rapidly swing its appendages in appropriate directions or use a gyroscope) in order to induce inertial forces that tend to right itself. Or, it can position one or more of its support members so that, as the vehicle falls over, they will contact the ground in a safe place and catch the robot before it hits the ground with portions of its structure not intended for ground contact. Note that these methods can be used in combination to maintain effective stability. With legged vehicles, this inverted pendulum situation and its control responses result during dynamically stable standing, walking, and the stance, or support, phase of running (Raibert, 1986). A wheeled vehicle example would be a unicycle.

For the unstable case of when no supporting members are in contact with the ground and the vehicle center of gravity follows a ballistic flight trajectory (such as when a legged vehicle runs), the robot needs to actively or passively control several parameters in order to maintain effective stability. Specifically, these parameters include the lift-off thrust and direction at start of the leap or stride, the body orientation during flight, selecting safe “landing areas” for its support members, guiding support members to these safe areas as it falls, and regulating touch-down forces.

An example of wheeled vehicles operating in a dynamically stable mode would be a motocross race where the riders on their “dirt bike” motorcycles frequently launch high into the air off of ramps in the racetrack. There are numerous examples of dynamically stable legged locomotion in the animal world, such as the galloping of horses in which none of their hoofs are in contact with the ground during portions of their locomotion cycle.

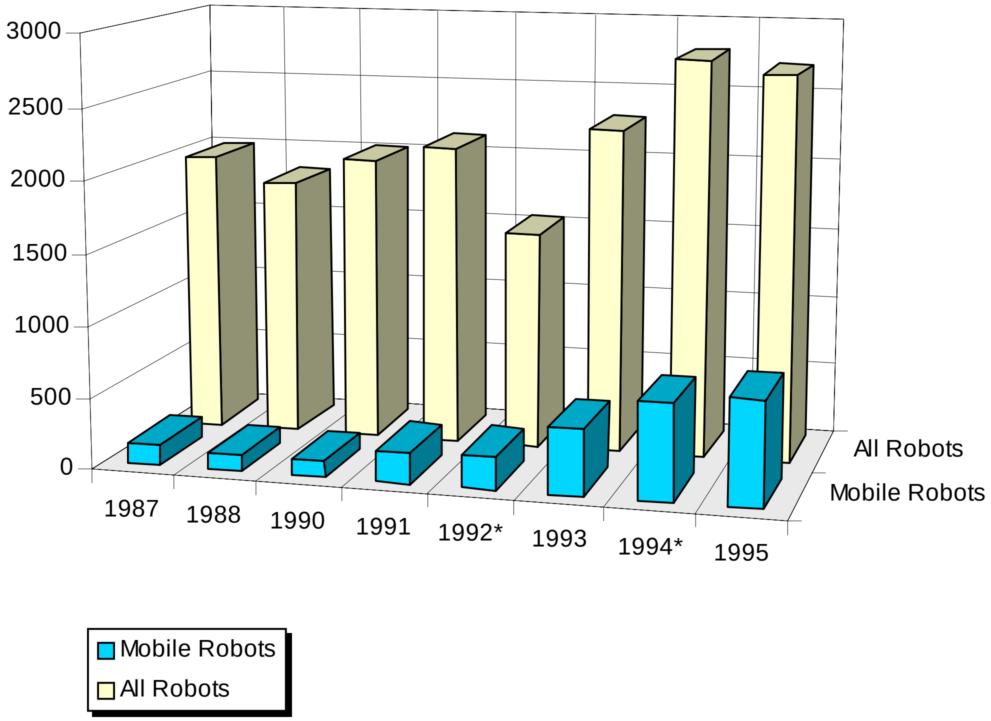
Dynamically stable running often involves several forms of energy transfer, whether performed by mammals (Alexander, 1990) or machines (Raibert, 1986). As Raibert (1986) explains it:

> ...there is a cycle of activity in running that changes the form of the stored energy several times: the body's potential energy of elevation changes to kinetic energy during falling, then to strain energy when parts of the leg deform elastically during rebound with the ground, then into kinetic energy again as the body accelerates upward, and finally back into potential energy of elevation.

In the following section, various examples of vehicles that utilize these stability modes will be described.

## *1.7 Review of Mobile Robot Morphology*

Mobile robotics has become a very active area of research in recent years. A search of the Comprehensive Engineering Index database for papers with the subject “robot*” compared to a search with the subject “robot* AND (mobile or vehicle or rover)” revealed that mobile robot research publication is growing both in numerical terms and as a proportion of all robotics research, (Engineering Information, Inc., 1987-1995). Figure 1.5 presents a year by year comparison of the number of papers about mobile robots and the total number of papers concerning robots generally. For example, during 1990 there were 113 papers pertaining to mobile robots out of a total of 2008 papers published on robotics in general. In contrast, 732 mobile robot papers out of a total of 2700 general robotics papers were published in 1995. Thus, between 1990 and 1995, the annual number of mobile robot papers published increased by 648%! Also, the annual number of mobile robot papers as a *proportion* of the total number of robotics research papers went from 5.6% in 1990, to 27% in 1995.



Note: Data was extracted from the EI COMPENDEX database.
* Data was unavailable for December 1992, December 1994, and all of 1989.

**Figure 1.5 — Year by Year Comparison of the Number of Mobile Robotics Papers to the Total Number of Robotics Papers**

The design of mobile robots raises technological issues not found in traditional industrial robotics. In conventional robotics, the base of the manipulator is bolted to the floor and the location and orientation of every object of the system and its environment are known precisely. In contrast, mobile robots usually work in unpredictable, unstructured environments, with moving frames of reference. As a result, technological challenges abound in almost every aspect of robot vehicle design: physical design, kinematics, sensing, obstacle detection, terrain-map data structures, sensor fusion, navigation, path planning, trajectory specification, control hardware, control software, power management, and the integration of all these components and subsystems. Each of these challenges has fostered a large body of research. This dissertation, however, is chiefly concerned with the morphology of mobile robots and its effect on motion programming and rough terrain mobility.

The remainder of this section concentrates on the morphology of mobile robots and includes literature concerning robotic vehicles that are either multibody or have legs. Single-body wheeled vehicles are excluded from this discussion. For the sake of brevity, only a sampling of the available literature is presented here, focusing on projects for which prototype hardware was actually constructed.

### 1.7.1 Multibody Wheeled Robots

The multibody wheeled vehicles reviewed here possess actuated degrees of freedom between their individual bodies, unlike trains and trolleys, which have only passive articulation between individual cars. As a result, multibody wheeled robots can potentially traverse difficult terrain, such as stairways and cramped passages.

Waldron, Kumar, and Burkat (1987) described a 3-bodied, 6-wheeled autonomous robot with three rotary and one translational freedom between the front and middle bodies, and three rotary degrees of freedom (DOF's) between the middle and last bodies. The vehicle was designed to be able to self-recover from an overturned position.

Hirose and his colleagues at Tokyo Institute of Technology have constructed several “active cord mechanisms” or ACM's (Hirose and Morishima, 1990; Todd, 1985). The ACM III has 20 bodies connected in a lengthwise chain with 3 rotary DOF between them. However, the pitch and roll freedoms are passive; only the yaw freedom is actuated. Each body of the robot has un-powered wheels attached to its bottom. The ACM III achieves locomotion in a manner similar to that of snakes. Specifically, a series of yawing “wave” motions starting at the fore and proceeding to the rear of the robot generates the propelling force. The ACM III is capable of locomotion through mazes and other complex planar terrain, but is essentially limited to operating on 2-D terrain. Hirose also constructed the ACM IV robot, which has 8 bodies connected in a lengthwise chain, with joints having 3 active rotary DOF’s. The design features an “exoskeleton framework construction” (Hirose and Morishima, 1990) that gives the robot a high load capacity and, in addition, yields a smoother exterior shape for the overall robot.

The Koryu, or KR 1, was constructed by Hirose and Morishima (1990) and was intended for use in inspecting nuclear facilities. The Koryu has six bodies connected together in a lengthwise chain. It has 2 DOF’s between consecutive bodies, consisting of a powered yaw and a powered **Z**-axis freedom. Each body is supported by a small track-laying chassis, which is powered by a DC motor. Collectively, these crawler tracks propel the robot. Each crawler track has both a passive pitch freedom and a dependent yaw freedom that is a function of the yaw freedom of the body it supports. The KR 1 can climb shallow stairs, travel across moderate lateral slopes, “stride” over obstacles, and cross over large ditch obstacles. Hirose and Morishima observed that robots with snake-like articulated bodies can have higher ratios of payload weight to frontal cross-sectional area, making them primary candidates for use in the narrow pathways of a nuclear reactor environment.

The U.S. Department of Energy funded a similar project to create a multibody wheeled robot that was also intended for inspecting and maintaining nuclear facilities. The Articulated Transporter/Manipulation System, (ATMS), is the work of a consortium of four universities and Odetics Incorporated, (Crane, Tulenko, and Bartholet, 1990). Like the Koryu mentioned above, it has 2 DOF's between consecutive bodies; however, its freedoms are pitch and yaw, whereas the Koryu uses vertical translation and yaw.

The Jet Propulsion Laboratory built a Mars Rover prototype based on a 3-body configuration (Puttre, 1991). The vehicle has six independent wheel drives (two per body). The robot is articulated by powered pitch and roll freedoms located at the connections between the bodies.

Chirikjian and Burdick (1993 and 1995a) constructed a 15-DOF robot that they used to test several forms of locomotion. The robot is composed of 5 identical modules attached end to end. Each module is a planar parallel mechanism with 3 DOF. Un-actuated, ratcheted wheels were attached between the modules. The ratcheted wheels were intended to "perform the same function as scales on a snake—they prevent retrograde motion while easily permitting forward motion" (1995a). Hence, although the vehicle used wheels, these tests demonstrated locomotion methods similar to those exhibited by inchworms, earthworms, caterpillars, and snakes. Because their work considered multibody legged locomotion, it will be discussed in greater detail later in Section 1.7.3.

### 1.7.2 Single-Body Legged Robots

Todd's book (1985) provides a good, general introduction to the field of legged robots. Raibert (1986) and Song and Waldron (1989) give chronologies of legged vehicle research. All three books provide large bibliographies. Oral (1994a) reviewed legged locomotion, concentrating less on chronicling major projects and more on providing a concise discussion of the salient research issues.

Several major walking machine projects have been based on a six-legged configuration. Marc Donner (1987) described a hexapod called the SSA walking machine that was designed and constructed by Ivan Sutherland. Donner also gave a shrewdly written in-depth look at real-time distributed control for this hexapod. The robot is self-contained, being powered by an on-board 18 hp gasoline engine. This engine drives four variable displacement hydraulic pumps, which, by means of 38 hydraulic valves, control the six legs of the robot. Each of the legs has 3 DOF.

Odetics, Incorporated developed several hexapod walking robots that have been proposed for use in inspecting and maintaining nuclear facilities (Carlton and Bartholet, 1987; Byrd and DeVries, 1990). The ODEX-I, ODEX-II, and the Robin each have 18 electrically powered DOF and can climb stairs. The vehicles can squat to enlarge their bases of support and increase their stability, and they can also stand higher and draw their legs inward in order to reduce their lateral cross-sections so they can pass through doorways.

Researchers at Ohio State University have built at least two hexapods. The first, called the OSU Hexapod, can traverse moderately uneven terrain by controlling the robot’s body tilt and by using active compliance control for the robot’s legs (Klein, Olson, and Pugh, 1983). A vertical gyroscope is used to measure the vehicle attitude and piezoelectric load cells are used to measure the leg axial forces. The active compliance control enables the balancing of forces in the legs while maintaining the robot’s orientation. The OSU Hexapod can adapt to irregular terrain without using an internal terrain model.

Numerous publications, the most comprehensive being a book by Song and Waldron (1989), have been written concerning a second Ohio State robot called the Adaptive Suspension Vehicle (ASV). The ASV is a large-scale (5 m long, 2600 kg) hexapod designed to operate in completely unstructured terrain. The legs use hinged planar pantograph mechanisms. Each leg has 3 actuated DOF plus a passive angular freedom at the ankle. Three legs are mounted on each side of the machine's longitudinal axis. The ASV power transmission and actuation system designs are especially notable because the vehicle has a self-contained power source. A 900 cc motorcycle engine supplies the power, which drives an energy-storage flywheel. Line shafts driven by the flywheel run down both sides of the vehicle towards the legs. The leg DOF's are actuated by a fully hydrostatic power transmission system. Each actuator is coupled to a variable-displacement pump powered from the line shaft by a toothed belt (Waldron, et. al., 1984; Song and Waldron, 1986; Waldron and McGhee, 1986).

A goal for the project was that the ASV would exhibit "horse intelligence" in the placement of its feet. An on-board operator controls direction, orientation, and velocity of the vehicle, but not the individual foot placements. The control system is operated in a body force mode in which sensed body motion is converted into force commands for the actuators of the supporting legs. In order to preserve stability, the vehicle must maintain at least 3 feet on the ground. Therefore, during locomotion, the typical stance of the vehicle involves controlling the forces in 9 DOF (3 legs) to support the rigid body of the vehicle which has 6 DOF. This redundancy results in a statically indeterminant system where the best distribution of leg forces is not easily determined. Recognizing this, the researchers (Waldron, 1986; Kumar and Waldron, 1988; Gardner et. al., 1990; Gardner, 1992) developed several algorithms for solving the force distribution problem, including approximate methods that are appropriate for real-time control. The vehicle is capable of maintaining effective stability using both static and quasi-static stability modes.

The Carnegie-Mellon AMBLER robot was designed for planetary rover applications, such as the exploration of Mars (Mahalingam, 1988; Bares and Whittaker, 1989; Dwivedi and Mahalingam, 1990; Simmons and Krotkov, 1991). The AMBLER has 6 legs, each of which has 3 DOF and a design that decouples horizontal and vertical motions for increased energy efficiency. The AMBLER stays redundantly, statically stable at all times; that is, it has enough supporting legs in the proper places, so that, even if one leg fails, the robot will not fall over. Unlike most earlier walking vehicles, the legs of the AMBLER have workspaces that overlap to a great degree, allowing the robot to operate even when some legs become damaged. The AMBLER robot was described in two configurations. One configuration has all 6 legs mounted so as to rotate about a central, vertical shaft. The second configuration has 3 legs mounted on each of 2 side by side vertical shafts with a central body cavity between the "stacks". This arrangement enables the AMBLER to use an unusual circulating gait with long strides, "where trailing legs recover through the body to become leading legs" (Simmons and Krotkov, 1991). The robot has a distributed control system with 3 CPUs plus 9 motion control boards for the actuators, and uses object oriented control software. It senses the terrain using a laser range scanner (like the ASV) and creates and stores a local terrain elevation map used for motion planning.

Researchers at Tokyo Institute of Technology have constructed a series of walking robots, including the PVII. The PVII robot has four legs attached to a central, "floating" body (Hirose and Umetani, 1980; Hirose, 1984). The legs were constructed from 3-D Cartesian pantograph mechanisms (PANTOMEC's), which improve walking efficiency because they decouple vertical and horizontal motions and do not waste energy via "geometric work". The addition of a rotational DOF about the pantograph's vertical axis allows 3-D mobility. An intricate control system structure was developed for the robot, in which a control hierarchy descends from navigation and planning through gait control to basic motion regulation. Basic motion regulation refers to the individual foot movements and placements. Search strategies were developed for the rectangular area available for a foot placement. A very elaborate search sequence gives the vehicle high terrain adaptability. Gait control was further subdivided into two levels. The higher level produces a motion trace of the body's center of gravity for a particular task. The lower level, called the adaptive gait controller, selects a gait for both high efficiency and adaptability of walking. Control design began at the lowest level and was reported to be complete up to the level of the adaptive gait controller, (Hirose, 1984).

More recently, Hirose and his colleagues have constructed the Titan-VIII (Arikawa and Hirose, 1996). A special emphasis of this vehicle design was to make it low cost and simple so that it could be used as a test-bed for many researchers. Each leg has 3 DOF and uses a cable and pulley arrangement to avoid the weight and expense of ball-screws, linear guides, and heavy toothed belts.

Raibert and his co-workers constructed a quadruped that could travel using a dynamic trotting gait (Raibert 1986; Raibert, Chepponis, and Brown, 1986). This work is a derivative of earlier research the authors had performed concerning a one-legged hopping machine. The application of two significant insights aided the extension of the earlier work to this 4-legged case. First, the control algorithms the authors developed for their one-legged robot can be applied to multi-leg robots whenever they use “one-foot gaits”, that is, gaits where the legs alternate so that no more than one leg provides support at a time. Second, two legs acting in unison and controlled to equalize their axial forces can be made to perform like a single virtual leg. Because that trotting gait involves synchronized pairs of legs, each pair of legs can be reduced to a virtual leg. Since the two virtual legs perform a biped one-foot gait, the process can then be controlled in a manner similar to their successful one-legged hopping machine. The authors suggest that two other quadruped gaits, the pace and the bound, could also be implemented using this technique because, like the trot, they use pairs of legs in unison.

Sony Corporation developed a quadruped robot modeled after household pets such as dogs and cats (Kitano et. al., 1998). Their goal was to establish a “robot entertainment industry”, and this robot was developed specifically to participate in the RoboCup-98 Paris soccer competition. Each leg has 3 DOF. As part of this work, Sony has developed a modular standard called OPENR™ that “enables reconfiguration of robot structure, as well as easy replacement of software and hardware components.”

Bipedal walking robots have been studied extensively in an effort to understand human locomotion and to explore the possibility of using them as prosthetic devices (Todd, 1985). Also, Furusho and Sano (1990) have stated that bipedal robots are “expected to be very useful in houses and factories designed for smooth human locomotion”. In general, biped designs have progressed from statically stable motion to more human-like dynamically balanced locomotion.

Japanese universities have been very active in bipedal walking robot research. Furusho and Sano (1990) listed 22 separate Japanese biped research projects. Waseda University has established the HUmanoid REsearch Laboratory (HUREL) for performing studies on biped robots (Yamaguchi, et. al., 1994).

A series of biped robots have been constructed at Waseda University. One of their more recent efforts resulted in a robot able to walk and adapt to a ground surface referred to as a “horizontally composed plane whose steps’ height is unknown” (Yamaguchi, et. al., 1994). Such a surface is often found in uneven flooring. In their experiments the robot took step lengths of up to 0.3 m while handling a step height of 12 mm.

Raibert (1986) and his colleagues at Carnegie-Mellon University have tested a tethered, planar biped capable of dynamic running at up to 4.3 m/s over flat, smooth flooring. Like the quadruped described earlier, this project was based on a prior successful one-legged hopping machine. The biped demonstrated that the algorithms used for controlling the hopping machine could be extended to multi-leg robots so long as “one-foot” gaits were used.

More recently, the Honda R&D Company developed two “humanoid” robots, the P2 and the P3, intended as prototypes for a general-purpose “domestic robot” (Hirai, et. al., 1998; Hirai, 1999). As the name implies, they are anthropomorphic, having two legs, two arms, and a head. The P3 is essentially an upgraded version of the P2. While the P3 is 14% shorter than the P2, it is approximately half the weight, consumes one-third the power, operates on battery power for twice as long, and has more reliable electronics than the P2. The designers carefully patterned the robots after humans. For example, they tried to make the leg link dimensions, the leg link centers of gravity, the joint locations, and the joint ranges of motion correspond as closely as possible to those of a human. Each leg of the two robots has 6 DOF. The robots are able to maintain a human-like posture by simultaneously using "ground reaction force control", "model ZMP (Zero Moment Point) control", and "foot landing position control". According to the authors, the robots can walk forward, backward, sideways, and diagonally, as well as walk on 10° slopes, and climb up and down staircases with step heights of up to 200 mm.

A 3-D one-legged "hopping" robot with 3 DOF's was built at Carnegie-Mellon University (Raibert, Brown, and Chepponis, 1984; Raibert and Wimberly, 1984; Raibert, 1986). This groundbreaking research focused on controlling the robot to be dynamically stable. The monopod consisted of an aluminum frame body, sensors, and a pneumatic cylinder leg. The leg was attached to the body by a gimbal-type hip having two DOF, hence giving the leg a total of 3 DOF. The monopod travels by hopping. Specifically, its locomotion cycle alternates between a ballistic flight phase during approximately 60% of the cycle and a support phase, during which the leg is on the ground, for the remainder of the cycle.

Effective stability for the hopping robot is maintained via dynamic stability. Controls for this condition were decomposed into three separate, simple parts: maintaining the body in an erect posture, regulating hopping height, and controlling forward running velocity. These three parts were then synchronized to operate the robot using a tabular approach. Specifically, the computationally intensive dynamics equations were precomputed and stored in tabular form. Then, in order to save computer memory, these tables were approximated using 40 and 68-term polynomial surfaces, which were then calculated at run-time (Raibert and Wimberly, 1984). The machine operates well on smooth, level floors, and demonstrates that effective stability can be maintained by active balancing. One version of the machine was programmed to leap over obstacles. These leaping tests were successful in approximately half of the trials, because, while the control system could control the height and span of hops, it was not made to control the take-off foothold position (Raibert, 1986).

Referring to single-body active-legged robots, Song and Waldron (1989) state that "both energy efficiency and mobility are closely related to leg geometry". In addition to the all-inclusive single-body legged projects listed above, several researchers have concentrated specifically on leg mechanisms. For example, Ryan and Hunt (1985) discuss both exact and approximate straight-line planar linkages and suggest those that have potential for use in legged vehicle applications. Lee and Raibert (1991) constructed a planar articulated leg similar to those of hoofed mammals such as horses. The leg was tested in a tethered arrangement in order to solve the problem of unwanted hoof rolling. Oral reviewed leg designs in two papers (Oral, 1994a, 1994b). In the second paper (Oral 1994b) he proposed a new leg mechanism called the Buraq, which can resemble either insect or mammal legs, depending on which alternate version is used. It is based upon the pantograph leg mechanism and inherits much of its advantages. However, Oral pointed out that the Buraq is suitable only for locomotion on obstacle free terrains because it cannot output an exact straight line and is "not fully controllable in the longitudinal direction". Alexander (1990) has conducted extensive studies on the use of tendons in animals and springs in mechanical legs for increasing the energy efficiency of locomotion. Specifically, he showed that tendons and/or springs can be used for temporary energy storage, energy transfer at the ends of strides, and as compliance for the feet.

### 1.7.3 Multibody Legged Robots

Multibody legged vehicles include two sub-types: designs that, in addition to their actuated multibody structures, have actuated legs, and designs that have non-actuated (passive or rigid) legs. Designs that have no legs and rest on their "bellies" are included in the latter sub-type.

#### *1.7.3.1 Multibody Active-Legged Robots*

Todd (1985) describes two octopods of similar geometry. The robots are composed of two rigid bodies, each of which has four vertically telescoping legs. The two bodies are capable of moving relative to one another with two degrees of freedom: a horizontal translation and a rotation about the vertical axis. One of the robots has magnetic feet and is used for ultrasonically inspecting steel pressure vessels. The other, constructed by Komatsu Ltd., is called ReCUS (Remotely Controlled Underwater Surveyor).

The Dante II robot was used to explore the Mount Spurr volcano in Alaska for nearly a week before falling over as it was climbing back out of the crater (Bares and Wettergreen, 1999). Like the two octopods described above and its predecessor, the Dante (Wettergreen et. al., 1993), the Dante II has two bodies or "frames", each having four legs. Each of the eight legs is a pantograph mechanism capable of raising and lowering its associated foot. The two frames are actuated so as to move relative to each other with both a horizontal translational freedom and a vertical axis of rotation of ±11°.

In order for the Dante II to crawl or "frame-walk", as the authors refer to it, the legs of one frame lift off the ground while the four legs of the other frame support the weight of the robot. The frame with the lifted legs then moves relative to the supporting frame by translating, rotating, or both. Finally, the legs of the moving frame lower to the ground, each adjusting to the underlying terrain. At this point, the frames reverse roles and the initially supporting frame lifts its legs and moves forward while the initially moving frame now supports the weight of the robot. Using this crawling motion, the Dante II was designed to climb slopes of up to 30°.

In addition to this basic crawling motion, the locomotion of the Dante II is enhanced by the use of a tether mechanism, which enables it to rappel up and down nearly vertical slopes such as those of the Spurr Mountain crater.

#### 1.7.3.2 Multibody Passive-Legged Robots

Chirikjian and Burdick (1995a, 1995b) coined the term "hyper-redundant" to describe robots having "a large or infinite degree of kinematic redundancy". They state that such robots "are analogous in shape and operation to snakes, elephant's trunks, and tentacles" (1994).

Chirikjian and Burdick produced a large number of publications intended to cover a breadth of issues concerning general hyper-redundant robots. They classify hyper-redundant morphologies into three types (1994):

1. Discrete, serial robots made up of "a large, but finite number of rigid links"
2. Robot's with actuation "distributed over the robot's length" and in which the "shape is continuously deformable"
3. Discrete, parallel robots made-up of a "cascade of parallel platforms" such as a Variable Geometry Truss (VGT).

Most of their work considers hyper-redundant manipulators, but in an internal California Institute of Technology report they also proposed the use of hyper-redundant robots for locomotion "without wheels, tracks, or legs" (Chirikjian and Burdick, 1990a).

They define two main types of locomotion for hyper-redundant mechanisms, namely, Stationary Wave Amplitude Varying (SWAV) locomotion, which is idealization of the inchworm locomotion, and Traveling Wave Amplitude Constant (TWAC) locomotion, which is similar to caterpillar locomotion (Chirikjian and Burdick, 1990a, 1991b, 1995a). In another paper, Burdick, Radford, and Chirikjian (1993) describe a sidewinding locomotion gait based on motion of desert snakes.

Chirikjian and Burdick (1995a, 1995b) approach the kinematics and motion programming of hyper-redundant locomotion based on a continuum model of a backbone curve, “which captures the robot's macroscopic geometry”. Using this method, locomotion is defined by first fitting a smoothed 3-D curve over the terrain path the robot is to follow. This terrain path curve is then offset to define the “spinal curve” for the robot, which describes the cross-sectional centroid of the robot. SWAV locomotion can then be produced by superimposing one or more curves that vary in amplitude onto the spinal curve. TWAC locomotion is produced by “transmitting a wave” of bending and/or extension and contraction along the backbone curve (Chirikjian and Burdick, 1990a, 1991b, 1995a). This approach results in an elegant method of planning collision-free paths over rough terrain (assuming the terrain perception is correct). Chirikjian and Burdick (1990a, 1991b, 1995a) also developed mathematical formulations for applying these locomotion types to both inextensible (fixed-length) robots and to extensible (expandable/contractible) robots.

What Chirikjian and Burdick (1995a) term the “terrain matching problem” refers to determining the time-varying backbone curve behavior to accomplish locomotion. In various papers they have proposed a number of alternative methods for solving this problem for both the inextensible and extensible cases.

For the inextensible case, the continuum backbone curve model is parameterized using a type of intrinsic geometry. Rather than using the classical intrinsic geometry method where 3-D space curves are defined based upon the intrinsic properties of curvature and torsion specified as functions of arc length, Chirikjian and Burdick (1994, 1995a) proposed specifying both curve tangency, using Euler angles (two angles defined in orthogonal planes), and roll as functions of arc length. This method enables determination of points on the backbone curve without having to solve the classical Frenet-Serret equations, for which there is no closed-form solution in the spatial case (Struik, 1950).

Chirikjian and Burdick have proposed two primary approaches for solving the terrain-matching problem for the case of inextensible motion: a modal approach and a calculus of variations approach. Chirikjian also reviews some additional methods of solving the inverse kinematics based on the continuum model backbone curve in another publication (1993).

With the modal approach, the configuration of the backbone curve is defined as a function of time by scaling a predefined set of “curvature mode functions” by an analogous set of time varying “modal participation factors” (Chirikjian and Burdick, 1990a, 1990b, 1994). Hence the terrain matching problem amounts to determining the modal participation factors at each time step. They discuss how to select the set of mode functions to avoid modal singularities and degeneracy (1990b, 1994). Also, because the use of mode functions may restrict the workspace of the robot to be “smaller than dictated by physical limitations” on the vehicle, the authors explain how the set of mode functions can be switched at run-time (1990b, 1994). In some simple cases, such as straight-line locomotion, solving for the modal participation factors at each time step can be done in closed form. However, for spatial motion over uneven terrain, it is generally not possible to solve for the modal participation factors in closed form. To solve the non-linear equations, Chirikjian and Burdick (1995a) proposed using a variety of methods. These solutions require iterative computations, and in some cases, nested iterative computations involving evaluations of the elements of a “modal Jacobian” matrix.

Chirikjian and Burdick also proposed a second method for solving the terrain-matching problem for inextensible robots. In this approach, "the calculus of variations is used to find the shape functions which cause the manipulator (here the locomotion wave segment) to satisfy necessary boundary conditions (the terrain boundary problem) while also minimizing a user defined criteria, such as the total bending of the backbone curve" (1995a).

Chirikjian and Burdick (1994, 1995b) appear to settle upon the modal approach as being the most computationally efficient and practical for use with a mobile robot, while the calculus of variations approach is considered most advantageous for determining optimal backbone shapes.

For the extensible case, in which the robot is desired to perform elongation and contraction motions, the parameterization of the backbone curve cannot to be truly intrinsic because local arc length varies. For this case, Chirikjian and Burdick define the kinematics of the robot relative to the terrain path curve, which was fitted to the underlying terrain over the intended path of the robot. Specifically, the robot backbone curve is parameterized by the arc length of the terrain profile curve, rather than its own arc length (1991b, 1995a). The backbone curve displacements and their timings to produce locomotion are then defined by specifying functions of time for: the wave shape, the wave height, the arc length positions of the front and back of the locomotion wave, and the arc length positions of the front and back of the backbone curve (1991b). In a later paper (1995a) they give two other methods for specifying motion. They specify longitudinal stationary wave locomotion on an extensible robot by defining a function for the location of the rear of the robot and a periodic function based upon an elongation distribution function that uses values for the gait period and stride length. And they specify a traveling wave gait for an extensible robot that combines contraction and bending by defining functions for the location of the rear of the robot, the elongation distribution, and the bending distribution, and by defining values for the stride length, the wave speed, the reference length of the active segment, the elongation factor, and the bending factor.

Regardless of the approach used to define the backbone curve at a particular time, a “fitting” algorithm is then used to match the geometry of discrete morphology robots (such as VGTs) to the shape of the continuum backbone curve (Chirikjian and Burdick, 1990b, 1991a, 1994, 1995b). Once the fitting is done, the inverse kinematics can be solved for each discrete module of the robot to determine the actuator joint displacements needed to accomplish the shape. Chirikjian and Burdick (1991a, 1995b) note that the inverse kinematics for the individual modules can be computed in parallel.

Chirikjian and Burdick (1993, 1995a) constructed a 30-DOF planar variable geometry truss robot to test their hyper-redundant algorithms. The robot is a modular design made of 10 truss bays, each having 3-DOF. Using this robot, they demonstrated traveling forward over flat, level terrain using several of the locomotion gaits described above. All of the hardware demonstrations presented in the papers show locomotion that requires continuous sliding of portions of the robot structure against the ground. This sliding is implemented with ratcheted wheels that allow forward motion but halt retrograde motion. Chirikjian and Burdick (1995a) state that the real time control of all 30 actuators was successfully implemented using a single Motorola 68030 processor.

In a different project, Kevin Dowling (1997) constructed a 20 DOF robot patterned after snakes. It has 10 bodies, or links, connected in series with a pitch freedom and a yaw freedom between the adjacent links. The robot has no roll freedom between its links, just as its natural counterpart, the snake, has no roll freedom between its vertebrae. The pitch and yaw freedoms are powered by actuators made from servos of the type used in radio-controlled models. Dowling also performed modeling and simulation of this robot, including a learning technique that optimized the robot's motions using a genetic algorithm and a probabilistic-based incremental learning method, with the goal of finding the gaits that optimized the “specific resistance” metric for vehicles proposed by Gabrielli and von Karman (1950). This process led to the discovery of several snake-like gaits as well as a number of new locomotion gaits not observed in the animal world.

A multibody crawling device was designed and constructed by students at Ben Gurion University under the supervision of Ben-Zion Sandler (1999). The “caterpillar” device has a series of seven body structures that are connected end-to-end. The adjoining body structures are connected by a single degree of freedom revolute joint that enables them to pitch relative to each other. The vehicle, which has no feet, is said to be able to move using several “bending modes”.

## *1.8 Relating the Literature to the Present Work*

Solving the all-terrain mobility problem involves creating a robot that minimizes the occurrences of the various modes of locomotion failure described in Section 1.5. Looking at the locomotion failure modes in reverse, what performance features must a vehicle possess to enable successful locomotion over extreme, rough terrain?

The graph in Fig. 1.6 shows some of the significant interdependencies between the desirable performance features (shown at the bottom of the graph) and the enabling technologies upon which they depend.

The rough terrain mobility of a vehicle is determined by several related factors, among which are: its terrain sensing accuracy in determining safe paths, or for legged vehicles, both safe paths and safe footholds; the available traction of its ground contact members (be they wheels or feet); the effective workspace of the ground contacting members so that the wheels or feet can reach the safe paths or footholds where they will obtain both sufficient support and traction for the vehicle; having appropriate control algorithms for assessing and preserving the effective stability of the vehicle; and having sufficient control bandwidth to both sense the stability state and react with proper actuation to preserve it within the (often brief) amount of time available for responding.

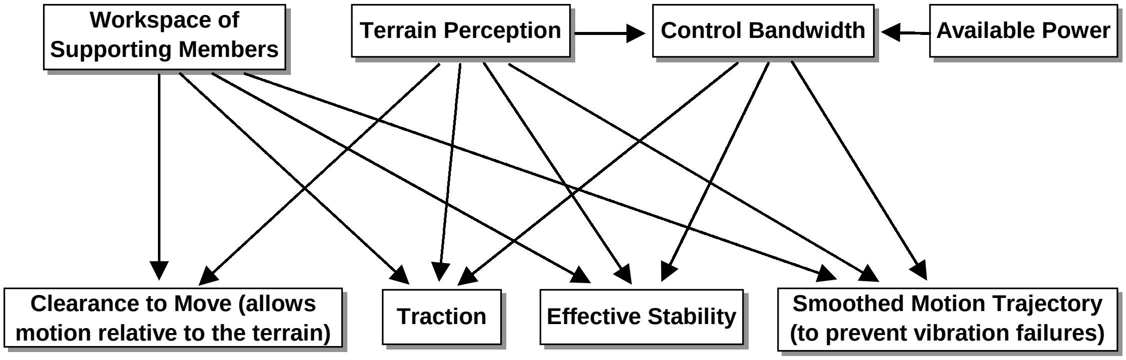


**Figure 1.6 — Enabling Technologies for Rough Terrain Mobility and Their Interdependencies**

While the graph in Fig. 1.6 depicts the basic design functions that determine the essential rough terrain locomotion performance attributes of a vehicle, it is clearly not exhaustive. For example, looking at the desired attributes, a traction failure will often have a negative effect on the stability of a vehicle. Other interdependencies also exist; for example, foot designs affect the traction of the robot, and the mechanism designs that determine the support member workspaces also influence the actuation bandwidth of the robot. Also not shown is the enabling technology of an appropriate set of control algorithms that must operate to orchestrate all of these mobility assets in order to accomplish the locomotion goals. Finally, at a more basic level, rough terrain mobility also requires that a vehicle have sufficient power to propel itself up steep inclines.

What is clear is that the rough terrain mobility problem is very complex and how best to achieve rough terrain mobility remains a subject of debate. The research cited in the literature used a variety of methods in attempting to accomplish rough terrain locomotion, focusing primarily on single-body, active leg designs that imitate the locomotion of adult arthropods. While great progress has been made on learning to walk and even run over flat, smooth surfaces and gentle terrain, reliable locomotion over extreme rough terrain remains an unrealized goal for man-made vehicles, regardless of whether wheels or legs are employed. Therefore, in this research, a different alternative for a legged vehicle will be explored.

### 1.8.1 Dynamic Stability Versus Static Stability

The method chosen to maintain stability is significant because of its crucial importance to mobility. To a significant degree, the mode(s) of stability that are employed restrict the choice of robot morphology.

With many animals, different stability modes are often used in different situations. For example, the same animal will use static stability, quasi-static stability, or dynamic stability depending on its relative desire for locomotion speed, locomotion efficiency, and stability margin of safety. However, mechanical vehicles may not have the same flexibility in choosing which stability mode to use because of limitations that may be inherent in the design of their control systems and in the overall design choice of their morphology.

The two primary stability mode choices are static stability and dynamic stability. Each method has its potential advantages. But which stability mode is the best choice for mobility over extreme rough terrain considering the limitations of currently available technology?

#### 1.8.1.1 Advantages of Dynamic Stability vs. Static Stability

Compared to static stability, dynamic stability offers three basic potential advantages for legged vehicles: greater latitude in the selection of foothold locations, the ability to maintain effective stability using intermittent support, and significantly higher locomotion speeds. All of these advantages are interrelated.

The greater freedom in foot placement provides several benefits. Raibert (1986) explains that, in a sense, dynamic stability can improve the mobility of robots because it relaxes the constraint imposed when using static stability mode of having to continuously maintain static equilibrium. Thus, dynamic stability enables robots to tolerate some instantaneous instability and yet still remain effectively stable. This can allow dynamically stable walking vehicles to use footholds that are widely separated from their centers of gravity. It also permits such vehicles to operate using fewer legs; in fact, they work best with 4 or fewer legs. Because dynamic stability can maintain the effective stability of robots without requiring large bases of support, it can enable robots to travel between closely spaced obstacles.

Much of the foothold flexibility described above is facilitated by the ability of dynamically stable robots to maintain effective stability via intermittent support. In addition, with proper motion programming, such vehicles can exploit ballistic motions to leap over obstacles in their path (Raibert, 1986).

Raibert (1986) pointed out that dynamic stability can enable vehicles to travel faster than vehicles operating in static stability mode. Specifically, the fact that dynamic stability provides effective support for the robot using fewer legs can reduce the support phase “duty factor” of the legs. Thus, legs can spend less time supporting the weight of the robot and more time moving forward. In addition, such vehicles can run by using phases of ballistic flight between long strides, thus achieving greater locomotion speeds.

### 1.8.1.2 Disadvantages of Dynamic Stability vs. Static Stability

While dynamically stable legged machines hold fabulous long-term potential (as demonstrated by the excellent rough terrain mobility of many vertebrate animals), their performance over extreme terrain is dependent upon having accurate knowledge of the terrain, maintaining sufficient sensing, control, and actuation bandwidth, and their ability to handle unforeseen events in a robust fashion (including the ideas of passive safety factors and active reflexive controls).

#### Terrain Perception

Raibert (1986) recognized the critical importance of terrain knowledge for legged locomotion; he stated:

> The single most important barrier to achieving useful legged systems that do not have direct human control is the task of determining the detailed shape of the terrain along paths of interest. This problem involves sensing, perception, and spatial representation. The difficulty of this problem is related to the generality of the situations in which the system will be expected to work. The speed of locomotion may also be a factor[JRS24].

The problem of obtaining accurate and timely terrain information is exacerbated by the computational difficulty of terrain perception. According to Bares and Whittaker (1989) "It is our experience that perception can consume 90% of the computing capacity of an autonomous mobile vehicle". Even locomotion over two-dimensional terrain still requires careful development of perception algorithms and limiting locomotion to slow speeds (Roman and Reinholtz, 1998).

The need for accurate terrain perception is a bottleneck limiting the rough terrain mobility of rapidly moving robots. Errors in perception can deceive the controller into selecting unsafe foothold locations, leading to instability and failure. Vehicles utilizing dynamically stable locomotion would achieve their highest speeds by using periods of ballistic flight. However, the dynamic nature of ballistic flight phases makes them inherently non-reversible; once in mid-air, a robot cannot turn back. Hence, such locomotion is generally not safe unless moving over a known path. For example, if a robot cannot see beyond the obstacle over which it is jumping to the next foothold location(s) on the other side, it is literally taking a leap of faith that may end in a damaging fall if there is, in fact, no safe foothold at the “landing zone”. Hence, the ability to step or leap over obstacles is limited by the need to “see” beyond the obstacle.

The need for timely terrain perception is a bottleneck limiting the locomotion speeds of robots. Because of their higher potential speeds, this affects dynamically stable robots more than statically stable robots. Specifically, safe operation at higher speeds will require more frequent updates of terrain geometry. However, this higher frequency results in having a shorter period of time available for sensing and analysis of each update. Moreover, for dynamically stabilized robots, terrain sensing will generally require measuring terrain geometry from a rapidly moving platform. Consequently, each terrain geometry measurement will be taken from a different frame of reference, further complicating the tasks of sensor fusion and spatial representation.

In contrast, the generally slower movements of static stability platforms will simplify these problems. In fact, some statically stable robots move intermittently so as to reduce the difficulty of terrain measurement and fusion of multiple sensor readings.

### Bandwidth

A key difference between static stability and dynamic stability is the time factor constraints each imposes on a locomotion system. For static stability of a legged robot, the sequence of movement events, especially leg steps, is important for producing an appropriate gait that will move the vehicle forward while avoiding tipping over. However, the rate at which this sequence of events is performed matters very little from the stability viewpoint. In fact, if a statically stable robot were to be frozen *at any time* during its locomotion, even mid-stride, it would remain stable.

In contrast, for a robot to be dynamically stable, not only is the sequence of actions important, but the precise timing of motions, especially the legs, is critical for preventing effective stability failures. If a dynamically stable robot were to freeze its body motions it would generally become effectively unstable on the very next stride. Failure to analyze the situation, send out the proper control inputs to the actuators, and then move the body and legs of the robot into position *in sufficient time* will result in an unrecoverable fall, impact with the ground, and possible, perhaps even probable, damage to the robot. Hence, there are critical requirements on the response time and the processing volume of the sensing/perception, control decision, and mechanical actuation tasks of the robot. These latency and throughput requirements can be referred to as the operational *bandwidth* of the vehicle system.

Achieving the sensing, control, and actuation bandwidth necessary to accomplish dynamically stabilized rough terrain locomotion is a significant technological challenge. Recall from Section 1.6.5 that dynamic stability involves “inverted pendulum balancing” and ballistic flight control. For the case of inverted pendulum falling, Donner (1987) states that “the minimum response time required to maintain balance is proportional to the square root of size”. He goes on to say that a 2 m tall human would require a response time of between 50-100 ms to remain within 10° of upright. Shorter animals and vehicles require even quicker response times. For the case of ballistic flight, if we disregard the case of operating in a low-g environment, it is hard to imagine a trajectory allowing more than 2 seconds or so for a control response. If additional jumping height is added to create longer flight times, the resulting impact forces upon landing would make precision control responses even more critical for avoiding damage to the vehicle.

Thus, the sensing, control, and actuation bandwidth requirements are significantly higher for robots operating in dynamic stability mode than for robots using the static stability mode. Furthermore, because of the generally faster locomotion speeds involved with dynamic stability mode, stability failures can have more severe consequences.

While a well-designed high-bandwidth controller could conceivably reject destabilizing disturbances that would defeat the simpler controllers needed for purely statically stable locomotion, there is nothing to prevent a statically stable vehicle from also having a high bandwidth controller that would take over in the unlikely event of instability. Thus, for maximum effective stability and safety, the ideal is probably to have a high bandwidth, dynamically aware controller, but to ordinarily operate the robot in static or quasi-static stability mode. Then, if the vehicle ever becomes unstable, the controller will switch to use dynamic stability techniques to recover from the fall before the robot impacts the ground and possibly gets damaged.

### Handling of Unforeseen Events

An all-terrain vehicle must be prepared to handle unforeseen events. Uncertainties in the perception of terrain, the kinematic model of the robot, the load-bearing capacity of the soil underfoot, and various random disturbances make unforeseen events inevitable.

These unexpected occurrences can destabilize a robot. For example, while a legged vehicle is traveling it could have a patch of ground fail to support one or more of its feet, a leg slip out from under it, a leg break, one or more of its feet hit the ground at a position and time unanticipated by the control system (e.g. trip over something), or it could simply lose its balance due to errors in motion planning or control. Any of these events could cause the vehicle to go into an unrecoverable fall and hence become effectively unstable. Confronted with such uncertainties, what is needed are either reflexive control algorithms to compensate for unexpected situations and/or safety factors in terms of vehicle stability.

Recognizing this need, Boone and Hodgins have worked on reflexive control methods. These methods provide more robust control of foot contact by operating without reference to terrain geometry, but instead, with only reference to proprioceptive joint information and foot contact forces. Specifically, Boone and Hodgins (1995, 1997) have worked on reflexive methods for stability maintenance and recovery when a robot is subjected to foot slippage on surfaces of varying coefficients of friction and to tripping over obstacles of varying heights. They presented impressive simulation results showing that these reflexive strategies can significantly reduce the frequency of effective instability.

Despite this substantial progress, however, like their natural counterparts (such as mammals), which have ultra-performance sensors and controllers, dynamically stable vehicles will inevitably sometimes fall. And because of the operating speeds and the inertias of such vehicles, they may fall hard and become damaged unless some way can be designed to make them invulnerable to such impacts without adding excessive weight. Such designs are difficult because, as Donner (1987) explained, small, lightweight designs require much higher bandwidth control systems to maintain balance. However, larger robots, with more reasonable control system speed requirements, must survive much higher impact forces because the potential energy due to gravity for a vehicle (or animal) scales with 4th power of size.

In his work concerning the AMBLER robot, Mahalingam (1988) observed that, no matter how accurate the terrain 3-D model, reliable determination of the load bearing capacity of a foothold area is not possible until weight is actually placed on a foot at that location. To deal with this uncertainty, he proposed continuously maintaining support via a “conservative support polygon” so that if any one leg or foothold were to fail, the vehicle would still maintain static equilibrium. Clearly, this method of providing a safety factor requires one or more redundant legs.

Because dynamically stable legged robots usually have fewer legs than statically stable legged robots, it is generally not possible for them to use redundant supporting legs for a safety factor. Hence, each foothold becomes much more critical for providing traction and support. Without this safety factor, dynamically stable legged robots have less tolerance for terrain perception and modeling errors, kinematic model errors (including those caused by bandwidth inadequacies), ground support failures, and other unforeseen circumstances.

#### *1.8.1.3 Static Stability: A More Reliable Choice Using Current Technology*

Due to the current inadequacies in sensing and controls technology and the lack of safety factors in the form of redundant legs in dynamically stable designs, static stability emerges as the preferred mode of maintaining effective stability when operating over extreme rough terrain. Therefore, the design presented in this dissertation does not pursue a dynamically balanced solution because, while dynamically stable mobile robots have tremendous potential for use on rough terrain when they can be made to perform, for example, like dogs or mountain goats, state-of-the-art dynamically stable robots are still, as of this writing, laboratory experiments used to explore the concepts of dynamic balancing and reflexive controls. This research seeks a practical solution to the all-terrain mobility problem in a less distant future. Hence, the stability mode and the robot morphology concepts pursued in this work are based on a simple life form, the caterpillar, that successfully traverses rough terrain using very little terrain perception. It is hoped that this will produce a "best of breed" statically stable solution to the all-terrain mobility problem.

### 1.8.2 Multibody Passive-Legged Morphology

From the literature review presented in Section 1.7, it is clear that the vast majority of prior legged vehicle research has focused on single body, active leg designs that imitate the locomotion of mammals and adult arthropods. In contrast, the morphology of the vehicle concept presented in this dissertation (and proposed and described earlier in Stulce, Burgos, Dhande, and Reinholtz (1990), Stulce and Reinholtz (1991), and Mele (1991)) is based upon a multibody passive-legged design that imitates the body structure and locomotion methods of a baby insect, the caterpillar.

While the vehicle concept presented here differs from prior mobile robot designs, it also embodies many characteristics that other researchers have recognized as advantageous for rough terrain stability and mobility. Specifically, because the crawling vehicle has a long-chain multibody structure similar to the body of a caterpillar, it has the clearance, traction, and stability advantages of multibody vehicles that were outlined in Section 1.5. Furthermore, the proposed vehicle has legs and feet, which are recognized by several researchers, including Bekker, McGhee, Todd, Waldron, Song, and Oral, as having the numerous rough terrain mobility advantages that were listed in Section 1.4.

Other multibody vehicle designs have either been frame-walkers or serpentine designs. The frame-walkers described by Todd, Bares, Wettergreen, Thorpe, and Whittaker have only two bodies with limited workspace between them, which is compensated for by the addition of active legs. The serpentine robots proposed by Chirikjian, Burdick, and Dowling have several serially connected bodies and considerable flexibility, but no legs. The crawling vehicle design presented here (Stulce, et. al., 1990) possesses some traits of both of the other multibody morphologies, but is itself unique.

Like the frame-walker robots, the crawling vehicle has legs and feet. However, the morphology of the vehicle presented here is a *passive* legged design. Its legs are not actuated; while they may have some passive freedom of motion for shock absorption and energy storage, they do not move in an actively controlled manner. The conceptual design of the vehicle multibody structure includes sufficient workspace such that the additional workspace provided by active legs would be unnecessary and hence would simply add needless complexity and weight.

Like the serpentine robots, this design has a redundantly actuated, serially connected multibody structure. This structure gives the vehicle a small frontal cross-sectional area per unit mass, an attribute cited by Raibert, Hirose, Morishima, and Dowling as enabling locomotion between closely spaced obstacles and through narrow pathways. Lastly, the lengthwise sequential multibody structure of the crawling vehicle can, with proper programming, enable it to perform cantilever and bridging maneuvers in order to span large ditch-like obstacles, as illustrated in Fig. 1.7 and Fig. 1.8. Hirose and Morishima also explored the potential of using cantilever and bridging maneuvers with their multibody wheeled robot, the Koryu.

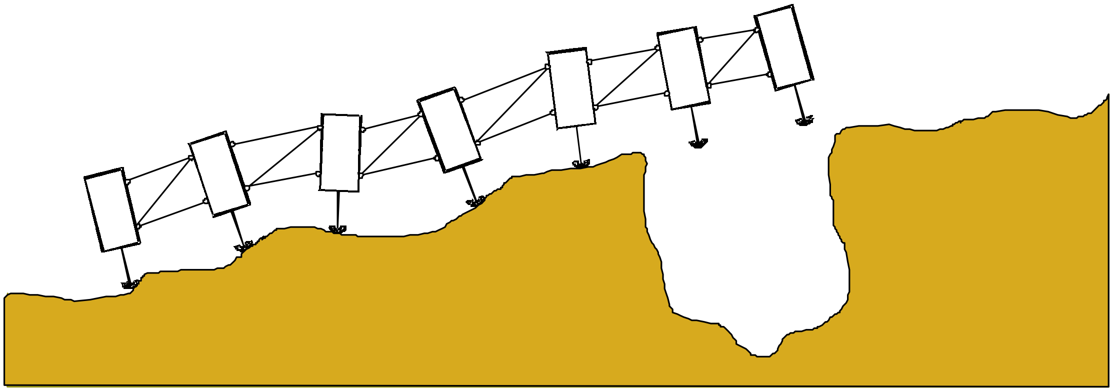


**Figure 1.7 — A Multibody Passive-Legged Vehicle Performing a Cantilever Maneuver**

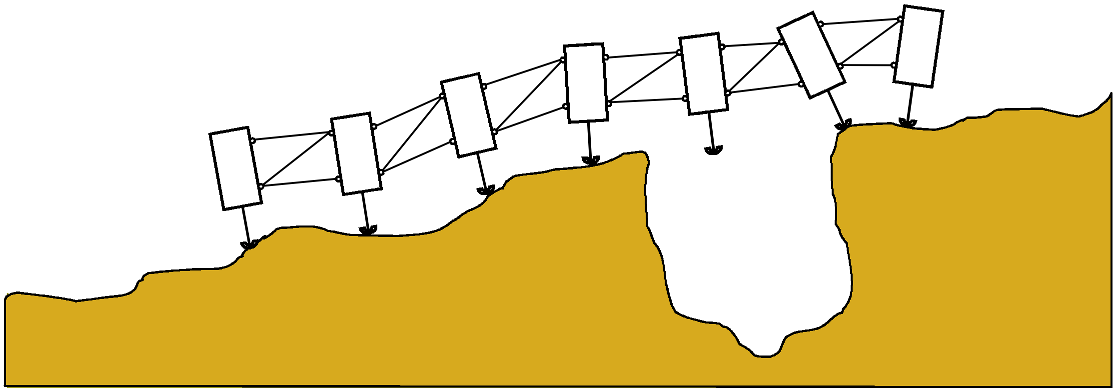


**Figure 1.8 — A Multibody Passive-Legged Vehicle Performing a Bridging Maneuver Across a Ditch-Like Obstacle**

However, unlike the designs of Chirikjian, Burdick, and Dowling, the design presented here has legs and feet. Having legs provides ground clearance, which, in turn, provides for contacting the ground at known points, namely, the feet. In contrast, legless robots use plate-like structures where the exact point(s) of contact may not be easily determined when operating over uneven, rocky terrain. Although using feet generally requires lifting them off the ground to move them forward, they provide excellent traction and avoid the necessity of dragging snake-scale-like plates across the ground (with their friction and wear difficulties) or having to use ratcheted wheels to provide forward-only rolling contact with the ground.

The crawling vehicle will have a minimum of eight feet, preferably twelve or more. This will reduce the consequences of terrain misperception and foot support failures, and will give the vehicle the safety factor described by Mahalingam (1988) as redundant static stability.

### 1.8.3 Similar Work

By far the most closely related research to this dissertation, both topically and temporally, is the work authored by Gregory Chirikjian and Joel Burdick that was reviewed in sub-sections 1.7.1 and 1.7.3.2. Chirikjian and Burdick performed research on hyper-redundant manipulators and vehicles, including motion specification, inverse kinematics, obstacle avoidance algorithms, trajectory generation, and construction and testing of a planar manipulator/vehicle. The locomotion methods described by Chirikjian and Burdick are more general than the approach described in this dissertation, which is specialized for the conceptual design presented herein. Nevertheless, their work includes a number of concepts similar to those presented in the papers that formed the basis of this dissertation (Stulce, Burgos, Dhande, and Reinholtz, 1990; Stulce and Reinholtz, 1991) and also in other papers written by the author's Virginia Tech colleagues Charles Reinholtz, Sanjay Dhande, Harry Robertshaw, Robert Salerno, Shahriar Tavakkoli, and Paul Mele. In addition to these topical similarities, the first public presentation of their "hyper-redundant" research occurred in the same year, 1990, as the first public presentation of the "multibody passive-legged crawling vehicle" research (Stulce, et. al., 1990), which laid the groundwork for this dissertation.

Chirikjian and Burdick's research on hyper-redundant locomotion was based on using a continuum model of a backbone curve "which captures the robot's macroscopic geometry", and then, for the case of a discretely segmented robot, partitioning and fitting its sub-assemblies to this continuous curve (1990a, 1991b, 1995a, 1995b). This was also the basic approach used in the work of Virginia Tech researcher Robert J. Salerno (from which this dissertation work evolved). Salerno and his colleagues' research concerned long-chain Variable Geometry Truss (VGT) manipulators, which are a type of hyper-redundant manipulator. They developed methods for motion specification and computation of the inverse kinematics for these manipulators based on the "shape control concept". This method involves specifying the basic shape of the robot using parametric cubic curves and then partitioning and fitting the discrete truss bays (modules) of the VGT to the curve (Salerno, Reinholtz, and Robertshaw, 1988; Salerno, 1989; Salerno, Dhande, and Reinholtz, 1990; Salerno, Reinholtz, and Dhande, 1991).

Chirikjian and Burdick defined the "backbone" curve of hyper-redundant manipulators and vehicles using a non-classical form of intrinsic geometry (Chirikjian and Burdick, 1989, 1994, 1995a). Similarly, Virginia Tech researchers Tavakkoli and Dhande developed computational methodologies for shape synthesis using classical intrinsic geometry for planar curves and a pseudo-intrinsic form for spatial curves. Their publications gave examples of fitting both planar and spatial long-chain VGT manipulators to intrinsically and pseudo-intrinsically defined curves, respectively (Tavakkoli and Dhande, 1990 (and later published in journal form, 1991); Tavakkoli, 1991).

Many of the gaits Chirikjian and Burdick discuss require ground contact members with large frictional coefficients in the rearward direction and low friction in the forward direction (1995a). In their locomotion experiments, the robot rolled on ratcheted wheels to accomplish these conditions (Chirikjian and Burdick, 1995a). In order to avoid the need for ratcheted wheels or other mechanisms to enforce the needed frictional conditions, they suggested a type of gait "combining synchronous traveling waves of elongation and bending" (1995a). This approach was also shown in the illustrations of the author's first paper (Stulce, et. al., 1990) and used in the work presented in this document.

Chirikjian and Burdick (1990a, 1991b, 1995a) also mentioned the possibility of using multiple simultaneous waves to achieve greater locomotion speeds. This technique was also suggested by the author (Stulce, et. al., 1990) and was observed being used by caterpillar specimens (Stulce and Reinholtz, 1991).

In some of their discussions on the inverse kinematics of hyper-redundant robots, Chirikjian and Burdick (1991a, 1995b) explained that a portion of the calculations are parallelizable, and thus different sections of the overall inverse kinematics problem can be simultaneously computed using several processors. The use of parallel processing for the kinematics of long-chain (VGT) manipulators was also proposed by several Virginia Tech researchers (Salerno, 1989; Salerno, Dhande, and Reinholtz, 1990 (and later published in journal form, 1991)).

Although many similarities exist between the work of Chirikjian and Burdick and the work presented here, there are also some important differences. The primary differences stem from the fact that Chirikjian and Burdick's research addressed general methods of locomotion for *legless* hyper-redundant robots operating in known environments, while this research focuses on a specific class of multibody passive-*legged* robots operating in uncertain and variable environments.

Chirikjian and Burdick developed their motion programming methods for a variety of legless robots. As such, it is unclear whether their methods would function well with the passive-legged design pursued in this research. The use of legs and feet provides ground clearance and hence reduces concerns about causing damage to the terrain and about needing to armor the bottom of the vehicle to withstand friction, wear, puncturing, and other terrain contact loads and stresses. However, the use of legs and feet also requires the specification and use of particular foothold positions to be most effective.

The various methods proposed by Chirikjian and Burdick provide no motion programming mechanism for the precise placement of arbitrary sections of the robot on specific safe terrain areas and hence cannot specify exact foothold locations or leg angles of contact relative to the ground surface. Although Chirikjian and Burdick developed an innovative method of obstacle avoidance via "tunneling", this method is only appropriate for "time independent workspace environments" where the “layout of obstacles in the workspace is well known” (Chirikjian and Burdick, 1992). Whereas, the problem here specifically involves an approximately known environment that may effectively shift as the perception of it changes or as the soil deforms under load.

Rather than using a backbone curve-based or shape control approach to define the overall geometry of a long-chain multibody robot as Chirikjian, Burdick, Salerno, and Tavakkoli had done, this research, from the beginning, has pursued a bottom-up approach more akin to the stepwise motion specification of other legged vehicle projects. The theory behind this decision was that this approach would allow the customization of footholds so as to better adapt to the terrain.

Chirikjian and Burdick developed an elegant high-level method of specifying collision-free trajectories for serpentine robots operating over undulating terrain. However, this method does not provide an adaptation strategy to account for the realities of an uncertain environment caused by errors in the kinematic model, environment model, and soil failures. The method of motion programming presented in this work includes the seamless integration of “guarded motions” to provide the adaptability required for operation in uncertain environments.

Using Chirikjian and Burdick’s modal approach, it is unclear whether a single set of mode functions can be chosen to describe all the possible motions required to operate over rough terrain, or whether the “mode switching” technique they described (Chirikjian and Burdick, 1990b, 1994) will be required. With the method presented in this work, there are no mathematically induced reductions of workspace. Hence, the method employed in this work does not require switching curve functions to reach different portions of workspaces.

The work of Chirikjian and Burdick can probably be adapted to the conceptual design presented in this research and made to serve as an alternative motion programming method for this class of robot. At this stage of research it appears that a backbone curve or shape control approach would probably be best for use with legless, serpentine vehicles, while the method proposed in this research would be best for the caterpillar-like passive-legged concept described here. However, this judgement may come into question depending on the final implementation of the algorithms, the final robot design, and the specific locomotion tasks the robot is to be programmed to accomplish.

### 1.8.4 Other Contributions from the Literature

Looking beyond morphology and motion programming issues, the research projects referenced in the previous sections include a great deal of work that is applicable to mobile robots in general. Therefore, the contributions of these projects in areas such as control system hardware and software, sensors, sensor fusion, map data structures, navigation, path planning, some of their terminology and methods of gait study, and methods of development and testing can be applied to the detailed design of future multibody passive-legged crawling vehicles.

## *1.9 Objectives and Scope*

This research seeks to address the all-terrain mobility problem by introducing a vehicle that imitates the remarkable rough terrain adaptability and stability of caterpillars. Furthermore, this work explores ways of developing this concept into a feasible technology. Specifically, this dissertation describes the conceptual design, motion programming, and creation of simulation-based configuration design tools for this unique class of mobile robotic vehicle, termed the multibody passive-legged crawling vehicle.

### 1.9.1 Stages of Design

Design is a selection process. This process can be divided into several stages, namely, the conceptual design, the configuration design, and the detail design.

At the conceptual design stage, designers seek to answer the questions, "What is the device? What tasks does it do? What components does it need to accomplish these tasks?" Thus, at this stage, the basic morphology of the device is selected, both in the structural sense and in a functional sense. The basic component types are selected and the connections between them are determined. The tasks to be performed by each component are selected and the basic functional relationships between these tasks are defined.

At the configuration design stage, designers seek to answer the questions, "What specific kinds of components are needed? How many of them will be required? How should they be mounted upon or within the device?" The most important attributes of the components are selected (for example, certain critical dimensions), the number of each type of basic component is enumerated, and the approximate relative positions of components within the product are decided. Thus, configuration design is generally concerned with selecting the *qualitative* attributes that the device and its components should have to best accomplish the design goal(s).

Finally, at the detail design stage, designers answer questions of, "What precise specifications should the components and parts of the device have to best accomplish the design goal(s)?" At this stage, the exact dimensions and materials for the components and their constituent parts are selected so that they have sufficient strength, stiffness, thermal conductivity, optical transmittance, or whatever other properties are necessary for proper functioning. Tolerances are specified for the parts so as to ensure proper clearances and fit between them. Algorithms and control laws are encoded for the selected control hardware. In short, designers make all the remaining choices required to make blueprints for manufacturing the device.

Thus, the detail design stage is mainly concerned with selecting *quantitative* attributes of the components and parts (such as size) in order for the device to best accomplish the design goal(s).

For example, in the conceptual design, it could be decided that the device should have an actuator. At the configuration design stage, this actuator is selected to be a DC electric motor rather than an AC electric motor, hydraulic motor, pneumatic piston, or internal combustion engine. Finally, at the detail design stage, the DC electric motor is selected to be an ABC brand, Model 12345, 12V, brushless DC motor.

The design process does not necessarily progress through these three stages in sequential manner. For many designs there are numerous feedback loops and retracements of the process as further alternatives are explored and design adjustments are made. However, it is well documented that the later design changes are made in the production process, the greater the cost in both time and money. Therefore, it is critical to make wise design decisions at the conceptual and configuration design stages.

### 1.9.2 Configuration Design Tools

With mature technologies, the configuration design for a new product is generally copied from some prior successful version of that type of product. For example, when designing another passenger automobile, designers already know from previous experience that, for the vast majority of applications, it is best for the car to have 4 wheels. But when dealing with novel technologies, the initial designs of a new class of product, configuration design issues are particularly critical. Such is the case with the multibody passive-legged crawler concept presented in this research.

While this research presents a conceptual design, a number of configuration design issues are still in question. For example, how many separate bodies and legs should the vehicle have? With what sequence and timings should the legs move to achieve the best mobility, where "best" can mean greatest speed, greatest stability, greatest efficiency, or some optimal combination of those attributes? However, at the configuration stage, the final product dimensions are unknown. Consequently, the part volumes, part masses, forces exerted, and other derived parameters can only be roughly estimated. Confronted with such uncertainties, it is crucial for designers to have appropriate tools to aid in the selection decisions of the configuration design. Fortunately, it is possible to discriminate between alternative designs by performing qualitative analyses, in which numerical answers may not have high *absolute* accuracy, but nonetheless have ample resolution to differentiate between the *relative* performances of competing configurations (Hazelrigg, 1999).

Qualitative analysis tools are useful, cost-effective means of optimizing the configuration designs of a new product. They enable designers to sift through the major configuration design alternatives early in the development process, rather than proceeding to the detail design stage or even the prototype stage of the process, only to find that the chosen configuration is unfeasible or has inadequate performance. These tools save time and money because they enable a faster, lower-cost search of the design space than more complex quantitative analysis tools. Thus, they facilitate a more thorough investigation of alternatives before proceeding to the expensive detailed design stage, generally improving design quality.

Thus, the simulation design tools developed in this work are primarily qualitative, answering questions concerning the relative efficacy of competing robot and motion program designs rather than being quantitative and attempting to give accurate absolute quantities for each competing design. In addition, rather than simply guess at vehicle dimensions and then check to determine if they work, the design tools created here also incorporate synthesis to derive some of the needed dimensions from the more basic given dimensions and motions the robot is desired to perform.

### 1.9.3 Scope of This Research

As noted earlier, the multibody passive-legged crawling vehicle is designed to be similar to caterpillars. Therefore, the gaits and motion programs investigated here will be limited to those that are caterpillar-like. Thus, other possible locomotion methods, such as sidestepping and some of the gaits discovered by Dowling (1997), are excluded.

Due to the similarity of the crawling robot to long-chain Variable Geometry Trusses (VGT's), the ability to perform bridging and cantilever maneuvers should be achievable by combining this research with the work of Salerno (or perhaps the work of Tavakkoli or Chirikjian and Burdick). The specifics of producing such maneuvers will not be covered here.

The specific goals of this research are as follows:

- to create a conceptual design of a new class of vehicle, namely, the multibody passive-legged crawling vehicle
- to study the locomotion of caterpillars in order to learn from those successful designs, because their body structure and locomotion are similar to the vehicle concept
- to develop mathematical models for use in the kinematics, motion programming, stability analysis, design studies, and visualization of the robot
- to develop a flexible method for programming the motions of the crawling vehicle, so that a variety of locomotion methods could be tested

- and finally, to create software simulation tools to aid in the configuration design of the robot and its motion programs, including the ability to produce visual renderings and animations of a variety of crawling vehicle/motion program combinations.

## 1.10 Overview

Finding a consistent, intuitive set of terms to describe this vehicle and its motion has been troublesome, even to the point of making conversation with other researchers difficult. This is mainly because this research is a combination of several other previously established, but until recently, unrelated fields of study. Thus, it could be appropriate to use some of the terminology of kinematics, static trusses, biological studies of animal locomotion, and single-body serial-legged walking robots to describe many aspects of the proposed multibody passive-legged crawling vehicle. For this dissertation, in general, the terminology of previous legged robot studies has been used where it applies to this new form of legged vehicle.

The following paragraphs provide an overview of the remainder of this dissertation.

Chapter 2 describes the conceptual design of the multibody passive-legged crawling vehicle, focusing on the rationale used to choose from among the candidate actuation mechanisms and structures for realizing the flexible body of the robot. The chapter also includes conceptual discussions of power sources, sensors, motion programming, and alternative control system methodologies.

As mentioned earlier, the natural counterpart most similar to this robot is the caterpillar. Chapter 3 describes a study of caterpillars conducted with the aid of slow-motion videotape footage. This study includes observations of caterpillar body dimensions, range of motion, gaits used for traveling over level terrain and crossing obstacles, and methods of rolling over. Several lessons of significance were learned from these tiny animals and were applied to the crawling vehicle design, particularly in the areas of overall body shape, gaits, and motion programming.

Chapter 4 describes the mathematical basis for a computer program to simulate and optimize various combinations of crawling vehicle designs and motion programs. This model includes parametric geometry to describe various physical designs for the robot, a system of coordinate frames of reference and transformations, a rapid calculation technique for the inverse kinematics, an algorithm for determining whether the robot will fall over during its locomotion, and a technique for computing the velocity and acceleration of all of the robot's actuators.

Chapter 5 presents a versatile method of programming the motions of the crawling vehicle. This method uses six dimensional parametric cubic curve trajectories and allows a variety of locomotion techniques (gaits and motion trajectories) to be programmed. New parameters for defining gaits for this class of robot and new equations for calculating the locomotion speeds of these gaits are also presented, as well as guidelines for motion programming.

Chapter 6 describes the simulation tools developed as part of this research, which embody the modeling, synthesis, and analysis techniques from Ch. 4 and the motion programming methods from Ch. 5, together with a user interface and code for displaying renderings and animations of robot motion. The chapter includes a discussion of the basic software modules, and explains their application to the configuration design of crawling vehicles.

In Chapter 7, the effectiveness of the simulation tools for resolving configuration design issues is demonstrated by the results of several examples. These examples include 3-D renderings of several parametric geometry designs, stability analysis of two gaits as they are put to use with several robots of different lengths, and three motion program test cases that compare caterpillar-like gaits with the author's initial gait concept.

Finally, Chapter 8 discusses future extensions of this research, and summarizes and concludes this document.