Small Planetary Rovers

Colin M. Angle and Rodney A. Brooks
MIT Artificial Intelligence Lab[1]
Cambridge, MA, USA

April 27, 1990

IEEE International Workshop on Intelligent Robots and Systems IROS '90

1 Introduction

We argue that small rovers on the order of I to 2 Kg are suitable for planetary exploration [Brooks and Flynn 89]. Not only are they extremely cost effective, but they also enable a number of new possibilities for scientific objectives .

We have previously built a small IKg ([Angle 89] and [Brooks 89]) six legged walking robot named Genghis. It was remarkably successful as a testbed to develop walking and learning algorithms. It encouraged us to build a more fully engineered robot with higher performance. We are building two copies of the robot, both 1.6Kg in mass. Their generic name is Attila. Attila has 24 actuators and over 150 sensors, all connected via a local network (the I^2C bus) to 11 onboard computers.

The robots are programmed in the subsumption archictecture (in actuality they are programmed in a higher level 'behavior' language).

2 Planetary Missions with Small Robots

In [Brooks and Flynn 89] we outlined the possible roles for small rovers in planetary missions. We discussed rovers ranging in size from a few kilograms down to tens of milligrams.

The Attila robots are prototypes for planetary rovers at the larger end of that scale. Since a principal cost of a planetary mission is payload mass, small rovers provide an immediate economic advantage. It is also possible to send more than one rover, perhaps tens, while maintaining the mass economy. This has two implications; redundancy reduces the need to have 100% reliability greatly reducing the cost of building each rover, and multiple copies of a single rover mean that the manufacturing techniques used can reduce the cost per gram of delivered robot.

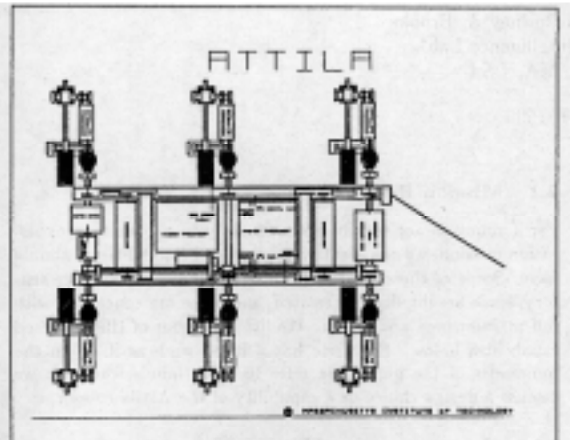

Figure 1: The Robot, named Attila.

The idea is to make the robots totally autonomous units. They are delivered to the planetary surface where they carry out their mission with no communication from the ground—thus the mass of a receiving and decoding unit is saved. A transmitter is onboard each robot and it reports back appropriate data and status information. The size of the support ground crew is greatly reduced, as there is nothing for such a crew to do! All that is necessary is to listen to transmissions.

2.1 Mission Requirements,

For a robot to act totally autonomously in a planetary exploration mission, we can identify a number of capabilities it should have. Some of these capabilities are locomotory, some are sensory, some are intelligence related, and some are concerned with self-maintenance and power. We list a number of these desired capabilities below. Each one has a label, such as ‘L2’. In the remainder of the paper, we refer to these labels whenever we discuss a design choice or a capability of the Attila robots.

2.1.1 Locomotion capability requirements

L1 It must be able to locomote over rough terrain. The smaller the robot is, the rougher the terrain will appear.

L2 It must be able to climb—it may well find itself in a crater, or blocked canyon when it lands, and furthermore, simple climbing may well greatly shorten its paths to particular goals.

L3 It must be tolerant of falls, and in particular be able to recover, in some way from a fall on its back.

2.1.2 Sensor capability requirements

S1 It must be able to sense its immediate environment well enough so that its actuators can reliably produce locomotion.

S2 It must, be able to sense the environment ahead well enough to plan paths around or over obstacles.

S3 It must be able to sense far off places as goals in order that its exploration becomes more than a simple local random walk.

S4 It must be able to sense the environment well enough to carry out its scientific mission of sending data back to Earth.

2.1.3 Intelligence capability requirements

I1 It must be able to plan local paths around or over obstacles.

I2 It must be able to select distant. goals and maintain a global heading towards those goals, despite local obstacles.

I3 It must be able to monitor its internal/external conditions and instigate appropriate maintenance behaviors.

I4 It must be able to intersperse locomotion acts with acts designed to carry out the scientific mission.

I5 It must be able to try things to recover from situations where it has become stuck or wedged.

---

[1] Support for this research was provided in part by a contract from ISX, in part by the University Research Initiative under Office of Naval Research contract N00014-86-K-0685, in part by the Advanced Research Projects Agency under Office of Naval Research contract N00014-85-K-0124 and in part by a gift from Siemens.

2.1.4 Maintenance capability requirements

M1 It must either have a lifetime energy supply on board (e.g., a radio-isotope thermal generator, or RTG), or it must be able to recharge itself (most likely using solar power).

M2 It must be able to keep itself unclogged by dust.

M3 It must be able to survive in a high radiation environment.

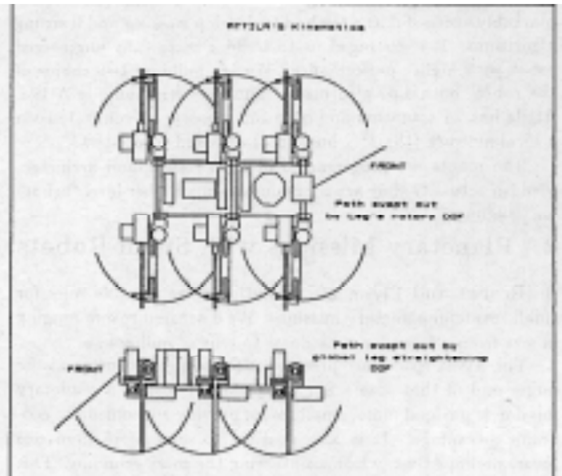

Figure 2: The kinematics of Attila's legs. There is one linear actuator and two rotary actuators on each leg.

3 A Physical Robot

The Attila robot is 14" long, stands 6" high, has 6 legs, one actuated whisker, and weighs 3.6 pounds. It carries over 150 sensors of 14 different types, all its own processing, batteries to power it for 30 minutes [M1], and enough solar cells to recharge it in 5 hours [M2].

3.1 Why Legs?

Much has been said concerning the advantages of legged vehicles over wheeled vehicles in regard to their mobility over rough terrain. [Waldron et at 84] [Hirose 84] [Hodgins 88]. We propose a second, perhaps more important advantage, especially for autonomous robots. Legs are much richer sensors than are wheels [S1]. The ability of a leg to sweep through and step in its environment can yield huge amounts of terrain information. Even with the crudest of sensors, Attila's predecessor Genghis, [Angle 89] was able to detect obstacles and their height, and feel out a path over them [L1]. Attila makes even better use of its legs by using them as sensor mounts. The 5 types of sensors mounted on a leg have their utility magnified because they can be swept about the robot's environment instead of being limited to a static mount.

3.2 Leg Design

Due to the size and weight constraints on the leg, it was not possible to use 3 non-backdrivable linear actuators on each leg as were used on many legged robots such as the PV II [Hirose and Umetani 80] the TITAN III [Hirose et al 84] and the OSU Adaptive Suspension Vehicle [Pugh et al 90]. Instead a mechanism with one linear actuator and 2 rotory actuators was used. The resulting leg design shown in figure 2 is characterized by reasonable efficiency, extreme mobility. Each leg weighs under 0.2 kg.

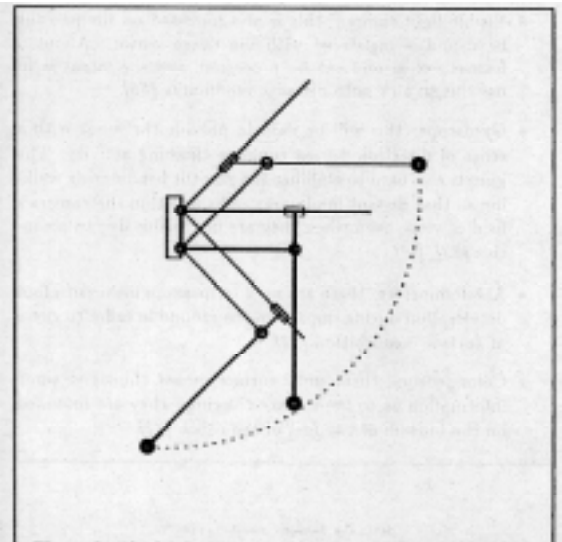

Figure 3: The leg in various configurations in its workspace.

The first axis of the leg is mounted vertically. This is important for the efficiency of the robot [Waldron et al 84]. When the leg makes a step, most of the motion of the leg is rotation about that first axis and therefore parallel to gravitational forces. Thus very little work is done against gravity. The leg, however, still must support itself. Since the lifting action of the leg is actuated only by a simple backdrivable gearmotor, the robot must expend power just to stand up. This problem was greatly reduced by adding a torsional spring in parallel with the motor to provide the needed downward force to stand. In pure statically stable walking, these springs decrease the power to lift the robot by over 60%. In the future, by using a dynamic walking gait the savings may be even higher [Alexander 90].

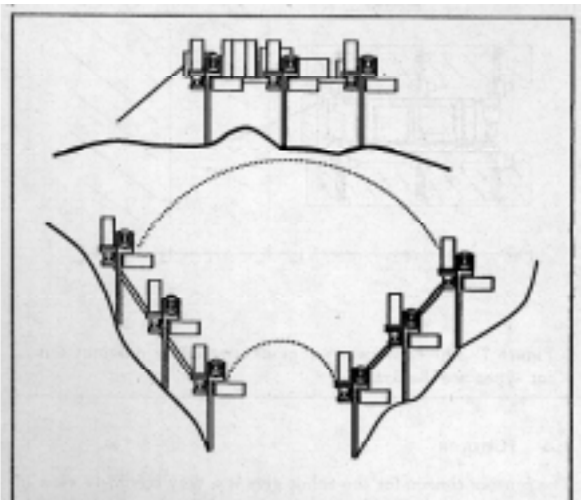

Figure 4: Attila's legs are servoed so that they are always vertical.

The leg design allows the foot a vertical reach of 8.5". This is a full 1.1 times the length of the leg as shown in figure 3. More importantly, with the foot at its maximum vertical height, the leg can push the foot downward with a force exceeding the entire mass of the robot (3.6 lbs). By using all 6 of these legs, the robot is designed to step onto a 10" high vertical obstacle. Again, scaling by the length of the robot's leg, it should be able to traverse obstacles 1.2 times its leg length [L1]. Comparing this step height to other robots which traverse rough terrain shows a factor of 1.5-2 improvement ([Pugh et al 90], [Hirose and Umetani 80], [King 90] [Bares 89]).

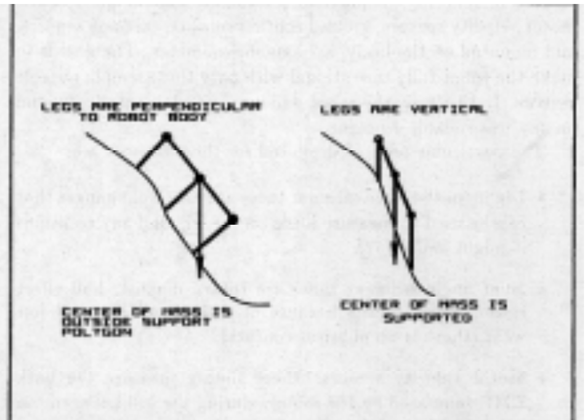

Figure 5: The fourth global degree of freedom keeps the center of mass of the robot under the polygon of support formed by the legs.

A fourth global degree of freedom links the rotation of all six legs about their axles together. The purpose of this is to ensure that the legs are always vertical. With the legs always vertical, the load on each of the leg motors is independent of robot inclination. This behavior is shown in figure 4. Vertical leg servoing also results in the lowering of the robot's center of mass and robot invertability [L2]. As the robot's inclination increases during a climb, the global rotation of the legs bring the center of mass of the robot closer to the surface being climbed. In this way, with no rotation about the leg's vertical axis, when the center of mass is within the polygon of support of the robot for any inclination, it is always within the polygon of support as shown in figure 5. The limiting factor for maximum climbable slope is friction of the feet on the climbed surface.

The Idea of allowing all the legs to rotate together was taken to its logical limit. They can rotate 720 degrees in either direction. If the robot falls onto its back, it can rotate its legs under it, and continue on its way [L3]. All sensors *which* care about their orientation are mounted on the leg axles, rotate with the legs, and then turn 180 degrees to face forward again if inversion occurs.

4 Sensors

Since the robot uses no a priori information about its environment, it must completely rely on its sensors.

The sensors are stratified into lower level sensors and higher level sensors as in figure 6.

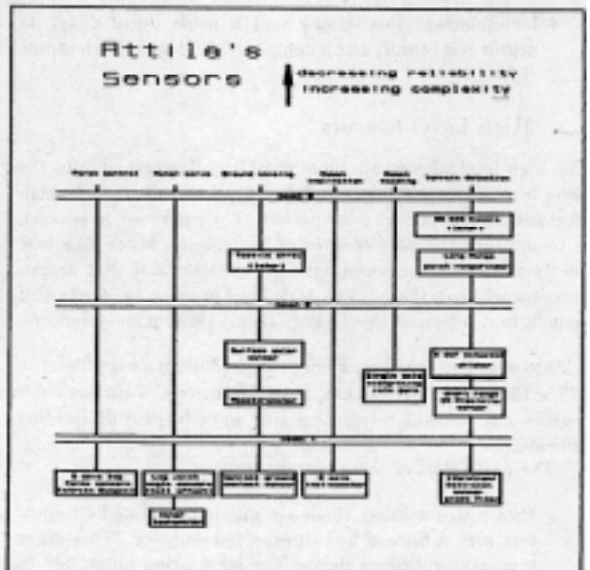

Figure 6: The sensors are stratified into lower level sensors and higher level sensors.

4.1 Low Level Sensors

The low level sensors are characterized by their reliability and accuracy. These sensors are very specific in what they sense, and their output does not need much interpretation. The low level sensors include leg mounted force sensors, joint angle sensors, motor velocity sensors, ground contact sensors, collision sensors, and mounted on the body, a 2 axis inclinometer. The goal is to make the robot fully operational with only these simple reliable sensors. In this way, the robot will never fundamentally depend on any less reliable sensors.

The particular technologies used for these sensors are:

- Leg mounted force sensors: these are foil strain gauges that can be used to measure loads on the leg, and any collisions it might suffer [S1].
- Joint angle sensors: these are rotary magnet, hall effect sensor pairs, chosen because of their small size and low wear (there is no physical contact).
- Motor velocity sensors: these simply measure the back EMF generated by the motors during the lull between the pulse width modulated drive signal.
- Ground contact sensors: these are extremely short range infrared proximity sensors used to anticipate footfall [S1].
- Inclinometer: this sensing unit is made up of a +/- 45 degree roll sensor, and a complete 360 degree pitch sensor [L3].

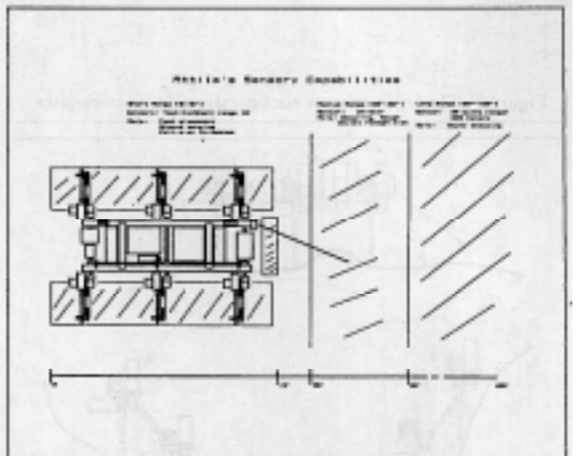

Figure 7: The exploratory regions covered by different sensor types are illustrated.

4.2 High Level Sensors

The high level sensors are more complex. However, due to the lower level sensors' ability to safely control the robot, these high level sensors do not have to be perfect. Their purpose, in general is to improve the performance of the robot. Much like how our eyes improve our performance, despite the fact that we can function without them. The high level sensors on Attila will include foot mounted short range (5cm) IR proximity sensors, a 25cm actuated whisker, a long range (3m) IR range finder, a 192 x 165 pixel CCD camera, 2 accelerometers, 2 surface color sensors and a small integrating rate gyro to provide heading information.

The particulars of these sensors are:

- Foot range sensors: these are simple modulated IR emitters with a filtered and thresholded detector. They sense imminent collisions during the leg's swing phase out to about 5cm [S2].
- Actuated whisker: this is a two degree of freedom scanning whisker which sweeps about in front of the robot. It provides information about obstacles right in front of the robot [S2].
- Long Range IR sensors: this is a linear PSD along with an IR emitter. It can triangulate distances out to about 3 meters, giving the robot a chance to completely avoid upcoming obstacles. It is mounted on a steerable pan tilt head.

- Visible light camera: this is also mounted on the pan tilt head and is registered with the range sensor. About 5 frames per second can be processed, and the intent is to use this to lock onto distance landmarks [S3].

- Gyroscope: this will be used to provide the robot with a sense of direction during complex climbing activity. The gyro is also used to stabilize the pan tilt head during walking so that distant landmarks remain within the camera's field of view, even when they are not visible due to obstacles [S3], [I2].

- Accelerometers: these are used to measure maximum foot deceleration during impact on the ground in order to guess at surface composition [S4].

- Color sensors: these small surface mount chips give some information as to the surface coloring-they are mounted on the bottom of two feet of the robot [S4].

4.3 Ranges

The sensors chosen for the robot give it a very complete view of its environment as shown in figure 7. The long range IR sensor and CCD camera yield information sufficient to distinguish a poor route over some terrain from a promising one. The whisker will be able to steer the robot around local obstacles, and the rest of the sensors will deal with the actual foot placement of the robot. In essence, the longer range sensors act as a terain filter which steers the robot toward routes which it should be able to handle. If the terrain filter fails, however, the robot's lower level sensors will eventually realize that the path which was chosen cannot be traversed, and the robot will search for another [S4].

5 Construction Issues

Attila's vast array of sensors brings with it a huge connector problem. The solution to this problem is the use of an array of microcontrollers. One of the controllers is located on each leg next to the sensors. Thus all the sensors on the leg need only have very short lengths of wire in order to bring its signal to the processor. The microcontrollers are all interfaced together with a serial bus (I^2C). The use of the micro controllers has reduced the number of wires coming off of each leg from 45 to 6. The 6 wires are protected by running them inside the frame of the robot.

Despite the reduction in the number of wires leaving the leg, there still are over 45 wires on the leg to route. This is done through the use of flexible PC board. Using a two sides flexible board, very high wire densities can be achieved (16 32 gauge wires in 0.5 cm). The flexible PC board also increases the reliability of the system since there are fewer wires around to get caught on something.

We are simultaneously building two Attila prototype robots. One of them is shown in figures 8 and 9.

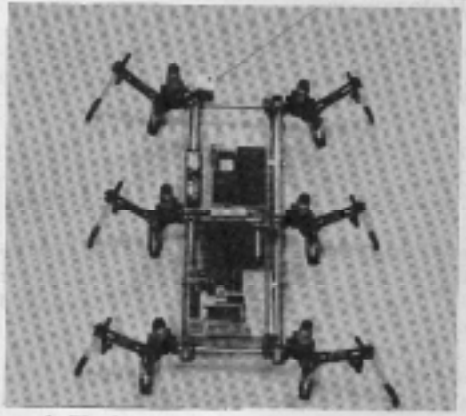

Figure 8: The first version of Attila, with the principal mechanical parts mounted. Prototype main processor and vision boards can also be seen. This photo was taken before wiring was added.

6 Programming the Robot

Attila is controlled by a seething mass of independent agents. This approach was successfully used in our first six legged robot [Brooks 89]. In that system we had a very distributed walking algorithm which let legs almost independently comply with rough underlying terrain, while still contributing to the maintenance of higher level goals [I4].

Attila has 9 servo processors which run the motors and sensor system. One main processor (a Signetics 68070) runs the subsumption architecture [Brooks 86, 90]. It simulates over 1000 independent asynchronous parallel processes, using a message passing protocol for communication [I1]. A second 68070 is dedicated to vision [I3].

In order to achieve the goals of the mission without having two way communication, or extensive ground support, it is important that the onboard processor be able to adapt to hardware failures in the extensive motor and sensor system. Thus many of the processes that run onboard the main processor are monitoring the health of the various subsystems. The subsumption architecture provides a natural way to accomodate dynamic switching out of sensors and actuators [I5].

As in [Connell. 89] there is little need for long term state. Thus we can afford to reboot the complete system at regular intervals. This limits the effect of radiation induced errors, meaning that it may be possible to use lower cost and less hardened processors than have traditionally been used on space vehicles [M3].

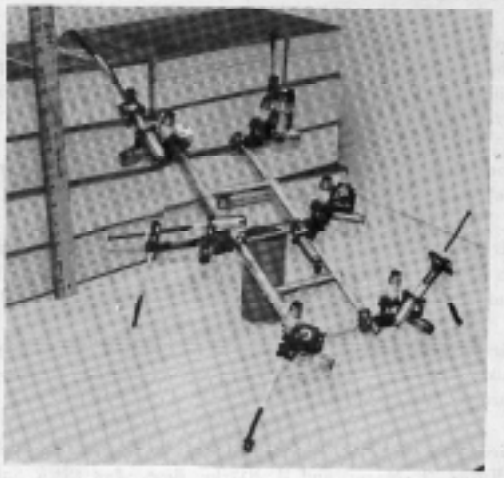

Figure 9: An unpowered Attila is placed in a climbing position to illustrate the reach of the legs.

7 Summary

Planetary exploration can be made cheaper by sending smaller rovers than is current practice. We are demonstrating the possibilities by building an extremely high performance, but nevertheless very small, totally autonomous six legged walking robot.

8 References

[Alexander 90] “Three Uses for Springs in Legged Locomotion”, R. M. Alexander, *International Journal of Robotics Research*, 9:2, April, 53-61.

[Angle 89] “Genghis, a Six Legged Autonomous Walking Robot”, Colin M. Angle, *MIT S.B. Thesis in Electrical Engineering and Computer Science*, March.

[Dares 89] “Ambler: An Autonomous Rover for Planetary Exploration”, J. Bares, M. Herbert, T. Kanade, E. Krotkov, T. Mitchell R. Simmons, and W. Whittaker, *IEEE Computer*, June, 18-25.

[Brooks 86] “A Robust Layered Control System for a Mobile Robot”, Rodney A. Brooks, *IEEE Journal of Robotics and Automation*, RA-2, April, 14-23.

[Brooks 89] “A Robot that Walks: Emergent Behavior from a Carefully Evolved Network”, Rodney A. Brooks, *Neural Computation* 1:2, Summer, 253-262.

[Brooks 90] “The Behavior Language; User's Guide?”, Rodney A. Brooks, *MIT AI Memo 1227*, April.

[Brooks and Flynn 89] “Fast, Cheap and Out of Control; A Robot Invasion of the Solar System”, Rodney A. Brooks and Anita M. Flynn, *Journal of the British Interplanetary Society* 42:10,478-485.

[Connell 89] “A Colony Architecture for an Artificial Creature”, Jonathan H. Connell, *MIT AI Lab, TR-1152*, June.

[Hirose and Umetani 80] “The Basic Motion Regulation System for a Quadruped Walking Vehicle”, S. Hirose and Y. Umetani, *American Society of Mechanical Engineers*, 80-DET-34.

[Hirose 84] “A Study of Design and Control of a Quadruped Walking Vehicle”, S. Hirose, *International Journal of Robotics Research*, 3:2, summer, 113-133.

[Hirose et al 84] “Titan III: A quadruped walking vehicle”, S. Hirose, T. Masui, and H. Kikchi, *Proc. 2nd ISRR Symp*. Kyoto, Japan, 247-253.

[Hodgins 88] “Adjusting Step Length for Rough Terrain Locomotion”, Jessica Hodgins, *Proceeding of IEEE conference on Robotics and Automation*, Philadelphia.

[King 90] “Personal communication with N. King Concerning the Odex I, II, and III”, N. King, *Odetics*, April.

[Pugh et al 90] “Technical Description of the Adaptive Suspension Vehicle”, D. Pugh, E. Ribble, V. Vohnout, T. Bibari, T. Walliser, M. Patterson, and K. Waldron, *International Journal of Robotics Research, 9*:2, April, 24-42.

[Waldron et al 84] “Configuration Design of the Adaptive Suspension Vehicle”, K. Waldron, V. Vohnout, A. Pery, and R. McGhee, *International Journal of Robotics Research,* 3:2, Summer, 37-48.