Reducing Software Mass Through Behavior Control*

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Abstract

A planetary rover, like a spacecraft, must be fully self-contained. Once launched, a rover can only receive information from its designers, and if solar powered, power from the sun. As the distance from Earth increases, and the demands for power on the rover increase, there is a serious tradeoff between communication and computation. Both of these subsystems are very power hungry, and both can be the major driver of the rover's power subsystem, and therefore the minimum mass and size of the rover. This paper discusses this situation in more detail, and discusses software techniques that can be used to reduce the requirements on both communication and computation, allowing the overall robot mass to be greatly reduced.

1 Differences Between Rovers and Research Robots

A planetary rover, unlike most laboratory robots, must be able to travel kilometers and operate for weeks or months with no more interaction from its designers and builders than can be provided by a sporadic low-bandwidth communications link. Perhaps the biggest difference between a real planetary rover and a prototype will be in the power subsystem. A real rover will not be able to run off an extension cord, have its batteries replaced, or new fuel put in its motor generator. A real planetary rover will almost certainly run off a radio-isotope thermal generator or off a solar cell/rechargeable battery system. The limits imposed by these types of power systems will most greatly affect the design of the rover's communications and computation/software subsystems.

1.1 The Need for Autonomy

If high bandwidth, real-time communications are available, not much is needed in the way of onboard computation. The operations of the rover can be teleoperated, and most of the onboard systems can be managed from the Earth. Unfortunately, at interplanetary distances, two factors prohibit the real-time control and operation of a rover from the Earth:

- the power requirements to beam sufficient data to the Earth from planetary distances can be very significant, or at least require excellent pointing accuracy on the part of the rover's antenna system

- at interplanetary distances, it takes minutes to hours for a signal to go from the rover to Earth, and back again.

Therefore, regardless of how much communications capability is available, the rover will have to be able to carry out many operations at least semi-autonomously.

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[*] This paper appeares in *The Proceedings of Cooperative Intelligent Robotics in Space III, SPIE 1992 Cambridge Symposium, Cambridge, MA, November 1992.*

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1.2 The Cost of Autonomy

After several years of work, a variety of autonomous vehicles have been created. These include DARPA's Autonomous Land Vehicle (ALV) a four ton eight wheeled single-bodied robot which navigated autonomously offroad over rolling hills, avoiding rocks, trees and cliffs; Ambler, a three ton six-legged walker developed at Carnegie-Mellon University [Simmons91]; and the Jet Propulsion Laboratory's Robby [Gat91b], a two ton six-wheeled three-bodied roller that navigated its way through the boulder fields and dry washes outside of JPL.

These and some other robots with similar designs are able to autonomously perceive the terrain, plan a path, execute that plan, and monitor their progress. To do these tasks they use computers capable of operating at hundreds of millions of instructions per second, and programs that are hundreds of thousand to millions of bytes in size. These robots are also capable of negotiating some terrain that is utterly impassable by the family car. The only major problem with using any of these designs for planetary exploration is their mass. A two ton rover requires a similarly sized lander. The transfer vehicle to boost the rover/lander from Earth orbit into a Mars injection is larger still. The booster to get the rover, lander, transfer vehicle, and their associated accoutrements would be of a size not seen since the Apollo landings. It would also be accompanied by an Olympian sized bill. The mass of these "intelligent" robots makes them too expensive to launch.

2 Lowered Costs Through Lower Mass

The obvious solution is to make the rovers lighter, and the most straightforward way to do that is to make them smaller. The motors, gears, structure, most of the electronics, and even the computers can be shrunk in size so that the robot weighs in at twenty kilograms rather than two thousand. But there are a few catches. If the wheel size of the rover is reduced from one-hundred centimeters to ten, you will also reduce the size of the obstacle that the rover can traverse by an order of magnitude.

2.1 Small Rover Mobility

This is not as much of a problem as it might at first appear. While a small robot will not be able to go over as many things as a large vehicle can, it will have an easier time going around things. Since the vehicle is smaller, it will be able to find paths through crowded terrain that would be difficult or impassable for a larger vehicle. Additionally, early research in the roughness of lava flows [Taylor91] indicates that the fractal dimension of many types of barren natural terrain may remain constant independent of scale (at least in the range of a few centimeters to several meters). Therefore, it is only appropriate to look at mobility in terms of overcoming obstacles that are a percentage of the size of the robot, not a fixed size. All in all, it might take longer for a small vehicle to get there, but in most situations it will get there.

2.2 The Problem of Small Rover Computing

The solution is not so rosy for reducing the computation subsystem. While the physical size of computers is constantly being reduced, that is at best only a partial solution. It is now possible to put very powerful computers (such as those used on Ambler and Robby) into a small package weighing just a kilo or two. Unfortunately, while the size has been greatly reduced, the power requirements to flip a bit or store a number in computer memory has stayed pretty much the same since the advent of CMOS a few years ago.

Modern computers compute by having the transistors in the integrated circuit change state. It takes a certain amount of power to perform this state transition; the amount depends of the material from which the semi-conductors are constructed. Current CMOS technology (which is the most power efficient technology currently ready for space flight) can deliver on the order of ten million bit operations per watt-second

The computers on Robby require several hundred watts to perform their computations. The batteries, solar panels and/or radio-isotope thermal generators to supply that much power on a continuous basis would mass dozens to hundreds of kilograms. So even though the computers can be made small and light, the power to run their software is very heavy.

The constraints that the power subsystem places of the software become more and more acute the smaller the rover, and therefore the smaller the power system, are made.

3 The Mass of Rover Software

RTG (radio-isotope thermal generator) technology delivers up to three watts per kilogram depending on the size of the power system. Solar technology when combined with batteries to handle shadows and night is usually not any more efficient for a rover on the surface of Mars. An autonomous rover must cycle through navigation and obstacle avoidance software for every unit distance traveled. To maintain an average speed of two meters per minute, prototype rovers (such as Robby) have had to execute tens of billions of operations per meter traveled. Looking at the efficiency of CMOS technology, and the mass of an RTG system, this can translate into tens to hundreds of kilograms of RTG mass, just to run the rover software. In order to reduce this mass, it is necessary to reduce the amount of software to run the rover.

The simple way to reduce the software for an autonomous rover is to make it less autonomous. However, this will not usually lead to a net power savings, since what is saved in computation power is lost on communication power and/or significant performance losses.

The other way out is to use a very different software methodology. Fortunately, such a methodology has been developed.

4 Behavior Control

A variety of robot control technologies have been developed that are significantly lower in computation than the traditional sense/plan/act cycle that has been used on Robby, Ambler, etc. These techniques include the Subsumption architecture [Brooks86], ALFA [Gat91a], reflexive control [Payton86], and several others. Collectively they are known as behavior control.

The main differences between behavior control techniques and more traditional planning techniques are:

- Traditional systems have several expensive processes that operate serially (the perception system feeds into the modeler which feeds into the planner, etc). Behavior techniques use robot capabilities that run in parallel (the goto goal, avoid obstacles, keep moving, etc behaviors all run all the time).

- Traditional systems make extensive world models, behavior control systems use minimal world models or none at all.

- Traditional systems are highly deliberative (they plan out sequences of action, and then compare the results of those actions to their expectations, and replan accordingly). Behavior control systems are highly reactive, and use a very coarse plan, if they use one at all.

- Traditional systems require tens to thousands of MIPs to achieve real-time performance. Behavior control systems typically use 0.1 to 1 MIP.

The last point above is the key one when discussing planetary rovers. While the difference in mass between the actual computing systems may be insignificant, the difference in mass for the power subsystem to support them can be enormous. On the low end a few tens of grams of an RTG system would be dedicated to powering the computation system. On the high end a few tens or hundreds of kilograms of RTGs would be needed for the computation system.

To a large extent, behavior control relies much more heavily on the intelligence of the robot system designer then it does on the encoded intelligence in the robot. The designer must carefully examine what classes of situations the robot will probably get into, and what are simple schemes for getting out of or negotiating those situations. Rather than decomposing the robot's activities into functions (e.g., perceive, plan, execute, and monitor) behavior control breaks the robot's activities and programs into sets of simple skills (e.g., move around obstacles, maintain a given heading, deploy the arm). The robot may not have any awareness that it is negotiating hazardous terrain to get a sample from a designated spot, but the interaction of all of these behaviors with the environment will result in that being accomplished.

Finally, experimental results have shown that behavior control can fulfill all the requirements of controlling a rover on a planetary like mission both in the laboratory [Brooks89, Bonasso91] and in a Mars-like setting [Miller92]. These experiments have shown that small rovers can be built and function autonomously with minimal communications, and only a few watts for their computation system.

5 Conclusions

As communications is reduced, whether because of distance or system capability, more autonomy is needed to get acceptable performance from a planetary rover. Early research on autonomous robots used a sense-perceive-model-plan-simulate-act cycle which was computationally very intense, if run fast enough to get useful performance. In the past few years, new approaches to autonomous control, called behavior control, have been developed. Behavior control techniques use an entirely different approach, and for many tasks will yield similar or superior level of autonomy to traditional control techniques, while greatly reducing the computational demand. A reduced computation demand means less power is needed for the computation system. Higher levels of autonomy mean that less demands are made on the communications system, and that power requirements can be reduced there as well. Since other aspects of a robot scale well with reductions in size, using behavior control allows the robot's size to be greatly reduced without losing capability. A smaller sized rover can greatly reduce the launch mass leading to less expensive, and more feasible planetary exploration missions.

As new mission architectures are designed that call for rovers massing only a few kilograms or tens of kilograms, the energy mass of the computation system can make or break a rover. If not carefully designed, the software can be the most massive part of a small planetary rover.

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