Reactive Navigation through Rough Terrain: Experimental Results*

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Abstract

This paper describes a series of experiments that were performed on the Rocky III robot.[1] Rocky III is a small autonomous rover capable of navigating through rough outdoor terrain to a predesignated area, searching that area for soft soil, acquiring a soil sample, and depositing the sample in a container at its home base. The robot is programmed according to a reactive behavior-control paradigm using the ALFA programming language. This style of programming produces robust autonomous performance while requiring significantly less computational resources than more traditional mobile robot control systems. The code for Rocky III runs on an 8-bit processor and uses about 10k of memory.

Introduction

The research described in this paper is motivated by NASA's planetary rover program. A planetary rover would be used on missions to deploy instruments and collect samples outside of the immediate area surrounding a lander. As science instruments get smaller and more sensitive, the size and strength demands placed on the rover by the instruments are commensurately reduced. The major constraints on the robot's size are then determined by the robot's ability to maneuver through the terrain, and the robot's ability to carry its own power, communications and computation.

Most of the pieces of a rover system scale well with reduced size. Communications, though, is an exception. As the size of the robot is reduced, it becomes more and more difficult to maintain a high bandwidth communications system. As communications capacity is reduced the rover must either operate with a reduced level of performance, or with greater autonomy [Miller90]. The computation system onboard a rover is also limited by the rover's size. The power requirements of the computers, and the mass of the power subsystem limit how much computation a rover can carry. In the past, autonomy has required enormous computational capabilities. It has been suggested [Brooks89, Miller91] that a reactive, behavior-based control system can reduce these computational requirements and still produce robust autonomous performance. This paper describes a working robot which confirms this theory.

The remainder of this paper describes Rocky III. Rocky is a six-wheeled robot massing about fifteen kilograms (see Figure 1). The robot carries all its own power (batteries that will run the robot for approximately ten hours), communications (a 9600 baud radio modem) and computation (a single 6811 microcontroller). An operator designates a sample site, and an optional set of intermediate way-points, and then sends the robot a signal to start its run. Once the start signal is received, the robot requires no further communications. The robot makes its way to the sample site via the way-points (if any were designated). When the robot reaches the sample site, it searches for and collects a sample of soft soil. It then returns to its starting point and deposits the sample in the collection container. If the robot should encounter any untraversable terrain during its travels, it modifies its course to go around those areas.

The next section describes Rocky III. Its mobility system, sensors, and computation system are detailed. Section three describes the software and algorithms we created for the robot. Section four describes the experiments and results that have been done with the robot. The final section presents some conclusions about the role of sensing and internal representation that can be drawn from these experiments.

Rocky III - The Hardware

The chassis of Rocky III is a six-wheeled springless suspension system called the "rocker-bogie" which consists of two pairs of rocker arms or "bogies". Each pair consists of a main rocker arm and a secondary arm whose pivot point is at the front end of the main arm.

*This paper appears in the *Proceedings of the Tenth National Conference on Artificial Intelligence*, AAAI-92, San Jose California, July 1992.

[1]This research was performed at the Jet Propulsion Laboratory, California Institute of Technology under a contract with the National Aeronautics and Space Administration.

Figure 1: The Rocky III Robot

Adjustable mechanical stops limit the rotation of the secondary arms. The two rocker-arm assemblies are connected through a differential gear at the center of gravity. The main arms pivot relative to the body and each other at the CG (See Figure 2). The main body of the robot is mounted on the differential. The pitch of the main body is thus the average pitch of the two rocker-arm assemblies, providing a more stable mount for instruments and sensors. An electronics enclosure mounted on the main body houses the robot's power distribution and conditioning system, fans, and a computer and interface boards.

The six thirteen-centimeter diameter wheels are independently driven by motors inside the wheels. The front and rear wheels are independently steered. For these experiments, Ackerman steering[2] was used to maneuver the vehicle, i.e., normals drawn from each wheel met at a common point. (See Figure 3.) The batteries were mounted in a pan below the differential. The mass of the batteries and the wheels and motors

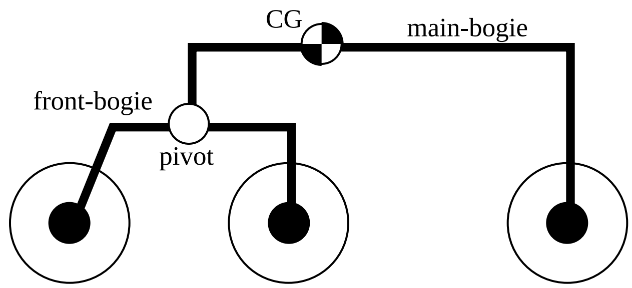

Figure 2: The Rocker-Bogie Mobility System

keeps the center of gravity at the differential or slightly below. There is a full wheel diameter of ground clearance below the battery pan.

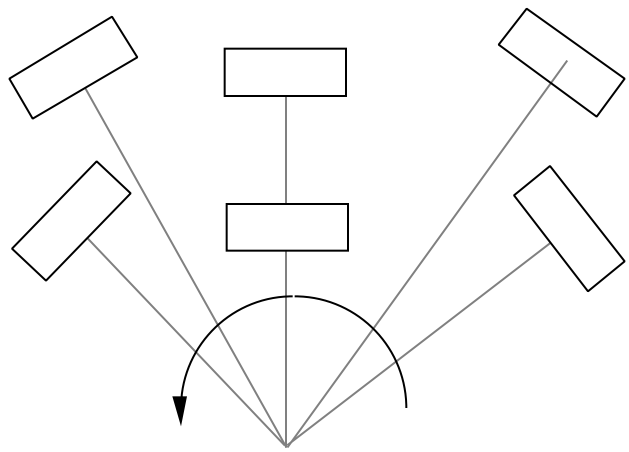

Figure 3: Ackerman Steering (top view)

At the front of the robot is mounted a three-degree-of-freedom arm. The end effector is a soft soil scoop. The arm can reach approximately five centimeters below the plane of the wheels in front of the robot, and folds to rest on top of the electronics enclosure when the robot is in motion.

The computation system is significant because of its limited capability. The only computer on board is an eight-bit Motorola 6811 processor with 32Kbytes of memory (though only about 10k bytes were needed for any of the experiments described in this paper). No mass storage is used. The processor and interface boards (for communicating with the sensors and motors) are all contained in a stack of five 2x4" commercially available boards. A 9600 baud radio modem is used to download programs and commands to the robot.

The sensors used on the robot are also very simple. A flux gate compass is mounted on a mast above the main body of the robot (to keep it away from the motors). (See Figures 4 and 5). The compass element is

[2]Ackerman steering assumes all wheels are in the ground plane. This assumption is not always valid for Rocky III, however, the errors induced by turning over uneven ground were insignificant and almost entirely removed when the robot servoed to a compass or beacon heading.

mounted on a float so that changes in roll and pitch up to twenty degrees do not affect its heading reading. The compass is accurate to approximately one degree of arc. Roll and pitch clinometers in the main body of the robot are accurate to about half a degree. Magnetic reed switches installed on the front-bogie pivots indicate when one of the rocker arms is at one of its limit positions. The two middle wheels are instrumented with one-count-per-revolution encoders. Since the robot would start its runs with its wheels in an arbitrary point in their rotation, it was possible to have a dead reckoning error (without slip) of up to a wheel circumference (approximately forty centimeters). Finally, there are mechanical contact sensors underneath the robot's bottom panel, and at the front of the robot.

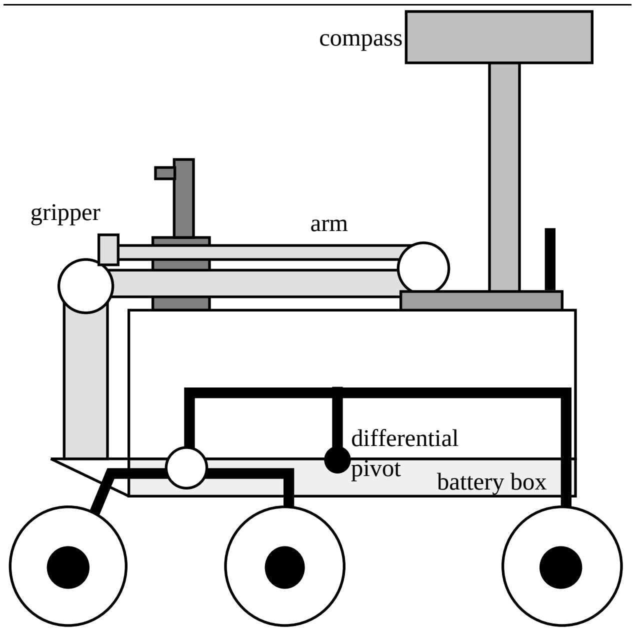

Figure 4: Side view of Rocky III

Rocky's arm has eight-bit position encoders on each of the three joints. Inside the end-effector are two contact switches used determine the hardness of the soil. One switch has a spike attached to it, the other has a flat plate. When the gripper is opened and pressed against the ground, the spike makes contact before the plate. If the soil is hard the switch with the spike will close on contact. If the soil is soft, then the spike penetrates the ground and the switch with the flat plate closes first.

Rocky also has an infrared beacon detector mounted on a rotating platform which senses a three-phase beacon mounted above the sample receptacle. The beacon is mounted on top of the lander (located at the starting position for each experiment). The single beacon consists of three sets of infrared LEDs operating at distinct frequencies which can be discriminated by the detector. Each set of LEDs is aimed in a different

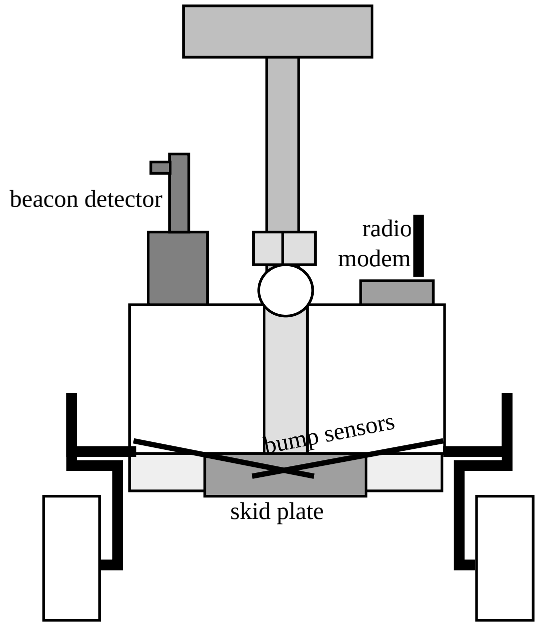

Figure 5: Front view of Rocky III

direction. By noting what frequency is received the robot can tell whether it is to the right, left, or aligned with the center of the beacon. The beacon detector can also determine the angle to the beacon using an eight-bit encoder on the platform, although this information was not used in the experiments. The beacon has a range of approximately five meters. The beacon is used only for end-point homing during the final phase of an experiment.

Rocky III - The Software

Rocky III is controlled using a software paradigm which has come to be called behavior control, which can be characterized by the following features:

- Behavior control tightly couples sensors to actuators through fairly simple computational mechanisms.
- Complexity in behavior control mechanisms is managed by decomposing the problem according to tasks (e.g. collecting a soil sample) rather than functions (e.g. building a world model).
- Behavior control mechanisms tend to manifest themselves as layered systems. Exactly what the layers do and how they should interact is the subject of much disagreement.
- Behavior control can be applied in situations where classical control theory is not applicable, either because the plant (i.e. the environment) cannot be modelled with sufficient precision, or because the complexity and dimensionality of the transfer function is too high to allow the mathematics to be carried through.

- Behavior control employs transfer functionals rather than the transfer functions of classical control theory, that is, the output of a behavior-based control mechanism can contain stored internal state (i.e. memory).

Rocky III is programmed in ALFA, a behavior language for designing reactive control mechanisms for autonomous mobile robots [Gat91a]. ALFA programs consist of networks of computational modules which communicate with each other and with the outside world by means of communications channels. Modules and channels are nominally dataflow devices, that is, they continuously recompute their outputs as a function of their current inputs. Modules can also contain stored internal state, allowing sequential computations to be embedded within ALFA's dataflow framework.

ALFA was designed to support a bottom-up hierarchical layered design methodology. In contrast to subsumption [Brooks86] where layers interact by suppressing communications in other layers, ALFA is designed to support an architecture where higher layers provide information to lower layers through interfaces which operate at progressively higher levels of abstraction.

The structure of the control software for Rocky III is shown in Figure 6. The lowest layer reads two input channels, which output a nominal vehicle speed and steering direction, and computes the settings for the individual drive and steering motors.

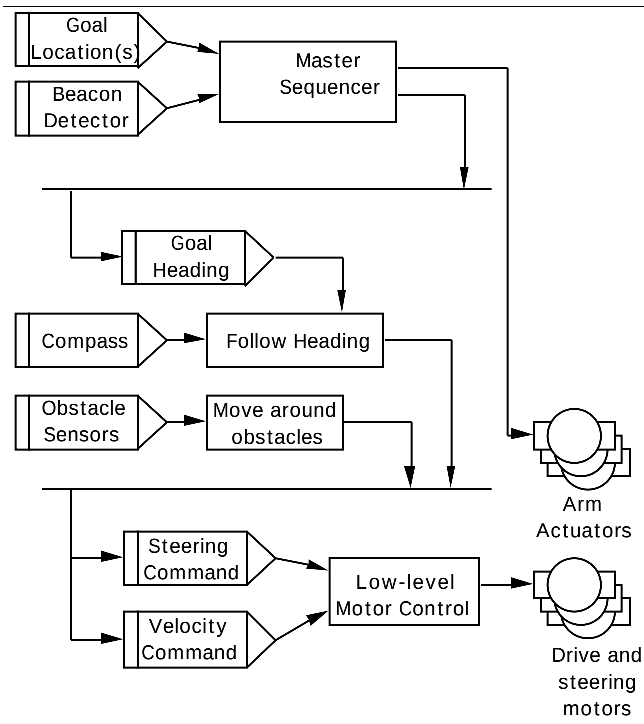

Figure 6: The Structure of the Control Software

The second layer performs two functions, moving to a commanded heading and moving around obstacles. Moving to a commanded heading simply involves computing the difference between the desired heading and the current vehicle heading as reported by the compass, and generating an appropriate steering command. Moving around obstacles is currently accomplished by backing away from the obstacle and turning to one side. This is a fairly simplistic strategy and could be improved, but field tests have shown this approach to be quite robust.

The third layer is the master sequencer which performs high-level control over the mission. On Rocky III the sequencer moves the robot through a series of way-points (goal locations), stops the vehicle, collects a soil sample, and returns to the lander.

The master sequencer collects input from the original task description (goal and way-points) and from the beacon. The closest thing to a map in Rocky III is manipulated by the master sequencer. The "map" is simply a list of X,Y points that give the position of the lander, the goal point, and the waypoints. The master sequencer uses these points one at a time to compute the robot's current heading. When returning to the beacon, the signal received from the beacon is used to compute the input to the goal heading channel. Depending on the signal from the beacon the robot will maneuver directly towards the beacon, at right angles to it (so it can line up on the center line), or head towards the best estimate of the beacon's position (when the beacon is out of range or occluded).

Experiments

The experiments performed with Rocky III were done to verify that it could meet certain requirements needed to autonomously carry out a planetary rover mission. These requirements include: being able to navigate to a designated area; being able to acquire a suitable sample; being able to negotiate obstacles (either by going over or around the obstacles); being able to return precisely to the lander and deposit the sample there; being able to operate with no real-time communication; being able to carry all power, computation, communications, etc.

Dozens of tests were performed to verify the robot's abilities. The experiments took place in a large indoor laboratory, and outdoors in the Arroyo Seco outside of JPL (a dry wash strewn with rocks, boulders, sand, and hard packed soil). All of the experiments had the same basic format, though the details of the robot's starting position and orientation, the positions of obstacles, the sample site and way-points differed from test to test.

At the start of an experiment, the operator downloads the sample site and way-points (if any) to Rocky. Each point requires four bytes. The positions are given in X-Y coordinates with the X-axis aligned to the centerline of the lander, and the origin at the front of the lander. The robot is given its starting location and the compass orientation of the lander. The operator then tells the robot to start.

As Rocky starts moving forward, it compares its current heading to the heading needed to get to the first way-point (or the sample site if no way-point has been specified) from its current location. It calculates the proper direction of turn and turns in that direction. This behavior is continuously repeated so that should the turn overshoot, Rocky will automatically correct its orientation. The robot keeps track of its position by using the wheel encoders and current compass heading to update its X-Y estimate.

As Rocky travels, it comes across rocks, ledges, and slopes of various sizes and degree. Any ledge or rock smaller than 13cm (one wheel diameter) is traversed by the mobility system. Ledges or rocks greater than a wheel diameter in size that are first contacted by a wheel, trigger one of the bogie switches. Rocks larger than a wheel diameter that go between the front wheels are detected by the skid plate or front contact switches. Severe slopes are detected by the roll and pitch clinometers.

When a section of untraversable terrain is detected, the robot executes an avoidance maneuver. It backs up, turns ninety degrees to the left or right (the opposite direction from the side of the vehicle at which the obstacle was first detected), moves forward a vehicle length (approximately a half meter), and then resumes its normal behavior. These obstacle detection and avoidance behaviors are active at all times and can override any other active behaviors.

When Rocky reaches the sample area, it deploys the sampling arm and tests the ground ahead of it for soft soil. If the ground is unsuitable, it lifts the arm, moves forward a few centimeters, and tests again. If suitable soil is not found within five trials, the mission is aborted, and the rover returns to the lander. When soft soil is found, the gripper closes around the sample, and the arm is retracted and stowed.

Using its current position estimate, the robot turns to a heading to bring it back to the lander. At the same time, it starts scanning for the lander beacon. The beacon consists of two sectors approximately forty degrees in angle, and a twenty degree center sector. Each sector's signal is modulated at its own characteristic frequency. When the beacon is detected by Rocky the robot heads straight towards the beacon if it detects the center sector, or it turns ninety degrees to the direction of the beacon, and moves towards the center sector, if a side sector is detected, until the center sector is detected. The beacon is then followed all the way to the lander. If sight of the beacon is ever lost (from occlusion), then Rocky reverts to navigation back to the lander by dead-reckoning.

The robot uses its front contact sensors to detect when it has docked with the lander. At this point it deploys the arm and deposits the sample in the collection container. Figure 7 shows key events during a typical experiment.

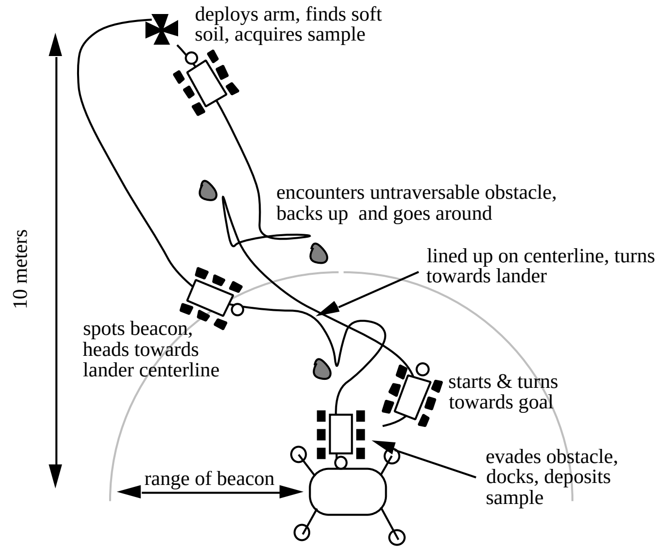

Figure 7: A Typical Run

After the software was debugged and tuned, dozens of runs were performed with only a few failures. Each of these failures involved hardware (a drive motor gave out, the beacon failed, a contact sensor was stuck on). In all cases the avoidance software succeeded in getting the robot through the obstacles and to the destination. For the outdoor runs, the vegetation was usually removed from the test area. But even during a run where the sample area was designated in a heavily vegetated spot, the robot eventually made its way around the large weeds and to the sample area.

Results and Conclusions

We have described Rocky III, a small mobile robot capable of autonomously and reliably navigating through rough outdoor terrain, acquiring a soil sample, and depositing the sample in a receptacle marked by a beacon. Such a capability has applications for planetary exploration. Planetary rover research has often emphasized innovative design to reduce power (eg., [Simmons91]). Rocky III's architecture allows the robot to be made small, and therefore lower power in all of its subsystems. Small robots are cheaper to launch, but because they cannot support high-bandwidth communications, must possess some level of autonomy.

Rocky III is the only example known to us at this time of an autonomous robot which operates off-road and performs both navigation and manipulation. The robot's performance has been demonstrated in dozens of tests in both an indoor laboratory setting and outdoor rough-terrain environments.

Rocky III is controlled by a small 8-bit processor using about 10K of memory. This is made possible through the use of a reactive behavior-control approach, where sensors are coupled directly to actuators through relatively simple computations. The control structure for Rocky III is extremely similar to that used on Tooth, our indoor object-collecting microrover [Miller90].

This work adds to the body of evidence for the claim that complex symbolic computations and world models are not necessary to produce robust, intelligent behavior in autonomous mobile robots. However, it must be pointed out that an absence of necessity does not imply undesirability. In other work [Bonasso91, Gat91b, Miller89, Payton86] the integration of reactive control mechanisms with symbolic reasoning has been shown to be able to increase the complexity of behavior over that which is capable from a straightforward reactive control implementation.

The success of the Rocky III experiments make another important point. Compared to most other reactive robots (eg., Herbert [Connell90]), Rocky III is sensory impoverished. The proprioceptive sensors (compass, encoders, and clinometers) tell the robot its orientation (and to some extent location) in space. However, all the information about the terrain that the robot is crossing comes from the bogie limit switches and the four contact switches on the front of the robot - eight single bit sensors. Rocky cannot sense the environment until it literally runs into it! Despite this handicap, Rocky is very capable of making its way through realistic and hazardous terrain. This capability is not connected to the robot's size (the roughness of natural rocky/lava terrain is independent of scale from a few centimeters to dozens of meters [Taylor91]). The robot's success is due to several factors. First, the mobility system is capable of handling most minor hazards. Second, the sensors, while very limited will virtually always detect a hazard that the robot cannot go over (though they might also generate false alarms). Finally, natural terrain is seldom a maze. Terrain is rich with paths, and it is not necessary for the robot to select the optimal path, only a path that works. If placed in a maze, Rocky might never make it out, but in real terrain it will succeed in almost all circumstances (it has not failed yet!). By limiting the scope of the robot to those environments it will realistically encounter, we have been able to simplify the sensing and computation systems of Rocky beyond those typical even for reactive robots.

Given the simplicity of the sensors and the programming, the question arises: "where is the intelligence?" The capabilities exhibited by this robot are a result of the entire robot system interacting with its environment. The sensors are simple, but they are the right sensors for this robot and this class of activities. By mixing the sensing and reactive capabilities appropriately with the mobility hardware's capabilities, and the class of tasks assigned to the robot, we have a robot that operates intelligently over its domain. The intelligence is just as much hardwired into the selection and placement of the sensors and the actuators as it is in the executed code, but it works just as well. The experiments described above show that an intelligently acting system can be created where the intelligence is in large part encoded in the device structure, rather than totally in the control/planning system.

Acknowledgements:

The authors wish to thank David Atkinson, Donald Bickler, Jack Fraisier, Nora Mainland, Jim Tran, and Brian Yamauchi for their significant contributions to this research.

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