MOBILE ROBOTS

Mobile robots are computerized mechanisms that move in and react to their environments in a way that is determined by some nontrivial combination of (1) human guidance (either prestored as some trajectory or plan of action or transmitted in real time) and (2) information derived from sensors that measure both the internal state of the robot and, more importantly, the external environment. Such devices have been built and studied since the mid-1960s for a variety of sometimes-overlapping purposes: pure research, military applications, commercial applications, hazardous environments, and space exploration. This article draws examples primarily from the latter application, since almost every issue in mobile robots is present in a most challenging form when one attempts to send such vehicles to other planets where the environment is truly unknown and no direct human intervention is possible.

HISTORY

The first mobile robot widely recognized as such was "Shakey," developed at SRI International (then the Stanford Research Institute) in Palo Alto, California in 1966, although other various vehicles such as missiles, torpedoes, and surface vehicles had been built prior to that time that might qualify as mobile robots by some definitions. Shakey moved in an environment with large artificial blocks that it could avoid, manipulate, and map. The performance of Shakey was sufficiently limited that one of the major conclusions of the project (in the early 1970s) was that building a useful mobile robot was much more difficult than had been imagined at the time. This conclusion was amplified in the mid-to-late 1970s when both the Stanford Cart and the JPL Rover (a testbed built at the Jet Propulsion Laboratory in Pasadena, California to develop techniques for exploring Mars with a mobile robot) were demonstrated using remote links to massive, state-of-the-art mainframe computers to enable very slow and fragile autonomous navigation. In addition to Stanford and JPL, some of the major contributors in mobile robotics since that time have been Carnegie Mellon University (CMU) [especially William (Red) Whittaker's group], Massachusetts Institute of Technology (MIT), (especially Rodney Brook's group), CNRS in Toulouse, France (groups led by Georges Giralt and Raja Chatila), the Universität der Bundeswehr München, Germany (Ernst Dickmanns' group), the Lunokhod and Marsokhod series built by VNII Transmash in St. Petersburg, Russia (A. Kemurdgian's group), and the succession of vehicles built by the US Defense Research Projects Agency (DARPA) under the names Autonomous Land Vehicle and Unmanned Ground Vehicle integrated by the prime contractor Martin Marietta Denver Aerospace (now Lockheed–Martin). Compendiums of some of the most important papers in the history of mobile robots can be found in *Autonomous Robot Vehicles,* (1) and *Autonomous Mobile Robots* (2). A good introductory text on the subject is *Mobile Robots: Inspiration to Implementation* (3).

MOBILITY PLATFORMS

The first and perhaps most important element of a mobile robot is its mobility platform. Mobility platforms which have been used or considered for mobile robots include wheeled vehicles, tracked vehicles, legged vehicles, hoppers, burrowers, and free-flyers.

Wheeled vehicles can be unicycles, bicycles, and so on. Unicycles are not quite as odd as they may first seem. The Robotics Institute at CMU has developed a gyro-stabilized single wheel which has modest mobility, and some years ago Arizona State University developed the concept of the "Mars ball," which was an inflated segmented sphere which achieved mobility by alternately inflating and venting various sectors. In all cases, the thrust of the unicycle depends on offsetting the center of mass of the vehicle from its geometric center. For reasonable wheel/payload mass ratios, it is very difficult for unicycles to climb over obstacles more than a few tenths of a wheel radius or over slopes more than a few tenths of a radian. Two-wheeled vehicles perform somewhat better than unicycles. With the two wheels side-by-side and with a dragging tail (much like old field cannons), they can climb over obstacles of about half a wheel radius.

Tricycles have better mobility than bicycles, but are very prone to tipover. The obstacle climbing performance of N-wheel vehicles depends on how many wheels are climbing (simultaneously) and on how much thrust the other wheels can exert on the climbing wheels. If the weight W of the vehicle is equally distributed on all wheels, and if only one wheel is called upon to climb (vertically) at any instant, and if the coefficient of friction of each wheel with the surface is u, then the simple-minded condition for the one climbing wheel of an N-wheel vehicle to lift off is when the weight on that wheel equals the lift due to thrust times the coefficient of friction: $W/N = u((N-1)uW/N)$. For $N = 3$, this requires that $u > 0.707$; for $N = 4$, $u > 0.577$; for $N = 6$, $u > 0.447$; and for $N = 8$, $u > 0.354$. Average frictional coefficients greater than 0.5 are not common in natural terrain; thus four-wheeled vehicles are marginal and six or more are needed for exceptional mobility. In the 1960s the focus was on possible lunar operations with the surveyor lunar rover vehicle (SLRV) shown in Fig. 1, developed for JPL by the General Motors team led by M. G. Bekker, author of the important text *Theory of Land Locomotion* (4). This three-cab vehicle had a very simple suspension using a single longitudinal spring and yet was able to climb over obstacles or cross chasms as large as 1.5 wheel diameters.

Another important criterion for a mobility chassis is tipover stability. Tipover stability is determined by how far the center of mass is from the edge of the vehicle horizontally and how high it is vertically. The most stable tricycle (an equilateral triangle) has a center only 29% of the longest vehicle dimension away from each edge, and so it is quite prone to

Figure 1. The General Motors/JPL surveyor lunar rover vehicle (SLRV).

tipping. A square four-wheeled vehicle has its center 35% of its longest dimension from each edge, and a hexagonal six-wheeled vehicle has its center 43% of the longest dimension away from each edge. (A circular vehicle would be most stable, with the center 50% of the longest dimension away from the edge.) The height of the center of mass is determined by the packing density of the payload, the mass of the wheels and running gear, and the height of the undercarriage. As a general rule of thumb, it is good to have an undercarriage clearance high enough to just clear an obstacle which, if it were under a wheel, would tip the vehicle just to the point of tipover. It is common for the height of the center of mass to be at or near the surface of the skid plate (since the payload is kept fairly compact above the skid plate and the running gear has significant mass below the skid plate). With this assumption, it is straightforward but tedious to calculate what the limiting obstacle height is for each of the N-wheeled vehicles in terms of the longest vehicle dimension. Thus one can produce a table of terrain friction requirement and limiting obstacle height as function of N. Four-wheeled vehicles have better climbing performance and better tipover stability than tricycles, as discussed above. However, they require an articulated chassis so that all wheels can support their share of the weight of the vehicle on uneven terrain and thereby prevent loading other wheels which might need to climb as well as giving their share of the needed thrust. Spring suspensions such as those found in the SLRV or automobiles don't do this very well since compression of a spring implicitly means that more weight is on this wheel (which is usually climbing) and the weight is correspondingly reduced on the other wheels (which are not climbing and therefore need to produce as much traction as possible). Thus the effect of a spring suspension is exactly the opposite of what one would desire.

JPL developed the rocker-bogie suspension to address this problem, and it used this type of suspension in a numbered succession of vehicles known as Rocky (the latest is a research vehicle known as Rocky-7 (Fig. 2); the Sojourner vehicle (Fig. 3) launched to Mars in December 1996 is Rocky-6). The rocker-bogie uses judicious placement of free pivots and swing arms to provide the necessary articulations (an N-wheel vehicle needs $N - 3$ articulations to have all wheels contact an arbitrary terrain surface). Computer optimization is performed on these configurations with a variety of obstacles to determine the best arrangement for particular applications. JPL uses mostly six-wheeled rocker-bogie vehicles as current and planned planetary rover testbeds. They have significantly better performance than four-wheeled vehicles, especially when the frictional coefficient is low or uncertain. Steering can be skid-steering (if helical flutes are used on the wheels to help pull them sideways), or two or four of the corner wheels can be steered. JPL has built eight-wheeled vehicles, and they have slightly higher performance than six-wheelers. They are skid-steered, or all wheels must be actively steered. The extra complexity and mass of the eight-wheel design seems not to justify the slight improvement in performance.

Tracked vehicles can have either segmented of elastomeric tracks. The segmented track is of course the conventional battle tank mobility mechanism. This tends to require significantly higher power (both peak and average) than wheeled vehicles due to entrainment of foreign matter into the running gear. This is justified if a huge power source is available and an extremely heavy vehicle must have its weight distributed over a large area to keep the ground pressure low. Conventional "dune buggies" typically have tire pressures of 5 psi; JPL planetary rovers are under 1 psi, and performance continues to improve down to 0.1 psi. The extremely limited power available to small autonomous vehicles will make segmented tracked mobility systems somewhat unattractive. In the 1960s and 1970s, Lockheed developed the "loopwheel" concept, where an elastomeric loop was stretched around two wheels, making a compact assembly which interacted with the ground, at least in terms of ground pressure and rolling

Figure 2. Long-range science rover (Rocky-7) during field tests.

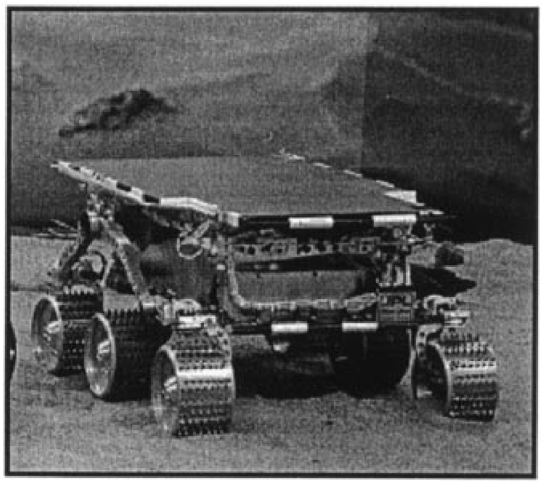

Figure 3. Sojourner rover flown to Mars.

friction, like a much larger wheel. Lifetime and foreign matter entrainment continue to be issues, although entrainment is less of a problem than it is with segmented tracks due to the lack of roadwheels running along the track down at the surface level. The drive wheels are well above the ground in the loopwheel system, and the weight of the vehicle is supported by the springiness of the loop, not by roadwheels which roll on the belt.

Legs have the advantage of being able to interact effectively with extremely complex terrain, and they are potentially very efficient. Biology provides many examples where legged vehicles have a specific resistance (joules per meter per kilogram) which is much lower than wheeled or tracked vehicles on rough terrain. Despite several decades of research, the energy efficiency of legged locomotion has never been achieved in machines, although the extremely complex control problems of football selection, placement, tactile evaluation, and failure recovery have been fairly well worked out by researchers at Ohio State University (OSU), Carnegie Mellon University (CMU), and Massachusetts Institute of Technology (MIT). High speeds require advanced power management, such as the flywheel/hydraulic system developed by OSU in the early 1970s. Still, complexity is a major issue because two or three actuators are needed for each leg. Bipedal walkers similar to humans are intrinsically unstable and complex to control. Quadrapeds tend to be slow when they move with a statically stable gait (one leg at a time), and they tend to be complex to control when they move with an unstable gait. For these reasons, hexapods have become the most popular legged mobility configuration in research and application. It has numerous useful gaits and offers a number of ways to deal with a single-leg failure. Most research vehicles have separated the actuators into (1) nominally vertical motions with high gear ratios and slow speeds and (2) nominally horizontal motions with low gear ratios and high speeds. The use of more than six legs is probably not worth the extra complexity, although it does allow multiple leg failures to be accommodated.

Vehicles have been built which roll on wheels on normal terrain, but which have their wheels on the end of moveable struts so that when the going gets rough, these struts can be used to provide lift or thrust or to increase weight so as to allow the wheel to get more traction. For example, JPL built a vehicle "Go-For" (Fig. 4) which had four wheels on struts which could be moved to shift the vehicle weight distribution off the climbing wheels and onto those wheels where traction was needed. With this approach, it was able to surmount obstacles as high as 70% of its longest stowed dimension. Another approach is to put wheels on wheels; some years ago, Lockheed put three wheels together in an equilateral triangle to form a major-wheel/minor-wheel configuration. Usually it rolled on two minor wheels, and the triangle did not rotate. When a large obstacle was encountered, the triangle rotated, putting the top minor wheel on top of the hazard and lifting the vehicle up onto the hazard. This allowed good high-speed performance on flat terrain with a system that was able to climb about 1.5 minor wheel diameters (about the same as a six-wheel rocker-bogie). Recently, JPL has built the "Nanorover" (Fig. 5), which has four wheels on four independently controlled struts, has an overall length of about 15 cm, has a

Figure 4. Go-For, a vehicle with wheels on struts.

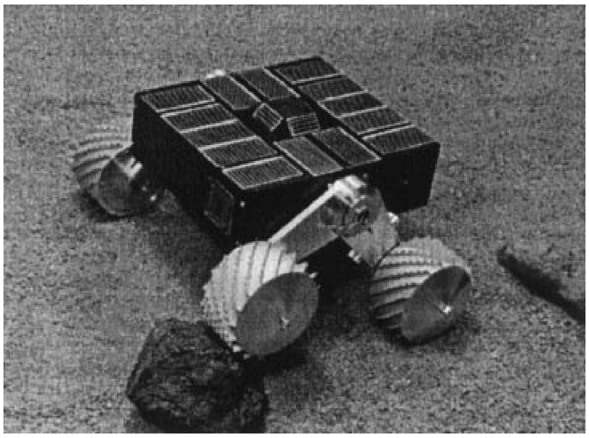

Figure 5. The JPL Nanorover.

mass of a few hundred grams, is self-righting, and is designed to "hop" long distances over the surfaces of small planetary bodies such as asteroids.

Ballistic hopping could be an effective and general means for surmounting many difficult hazards. For any other of the surface-traction mobility means described here, it is difficult to imagine how they might be simply designed to surmount the range of hazards which might exist in natural terrain. Hoppers with wheels seem especially attractive. A wheeled vehicle can maneuver over many types of benign terrain, but also has a chemical propulsion system, such as solid fuel pellets, for hopping over especially difficult hazards or extricating the robot from otherwise-fatal situations. That is, it might have a combustion chamber which is connected to one or more piston-cylinder devices for hopping.

Grappling hooks are also very attractive. They allow mobility up vertical or across long obstacle fields which cannot be surmounted in a single hop. The grappling hook would itself need to be equipped with actuators and sensors which allow careful assessment and repositioning so that an adequate strength hold is achieved, and so it can be released on command. One particularly simple alternative is a gun–hook–winch–skid system which has a single actuator for pointing the gun (in azimuth), the ability to fire the grappling hook, and then a winch to pull the vehicle up to the hook on skids. Such a system might have only three actuators and yet have phenomenal mobility if the terrain is such that grappling can be assured.

It is noted that ground effect machines have very poor slope climbing and high power requirements but can move over water or low masses of tangled material such as shrubbery or rubble; fixed wing aircraft have special needs relating to landing and takeoff as well as relatively high power requirements, whereas rotary wing aircraft are much better in landing and takeoff flexibility but have a very high power requirement; and rockets or jets can be very simple but have an even larger power requirement. Many underwater mobile robots have been built for exploration or military purposes; these generally consist of a pressure vessel containing the electronics and payload, some ballast system for buoyancy and attitude control, and some number of pointable screw thrusters for direction control. JPL is now building a subsurface explorer (Fig. 6) for exploring deep underground on Mars or other planets or small bodies. This vehicle is a long cylindrical tube with a massive hammer which literally pounds the vehicle through soil or rock. Another novel form of mobility is the "aerobot" (Fig. 7), a free-floating balloon which has (at least) the ability for the on-board computer to control the altitude using, for example, a phase-change fluid which condenses at the temperatures and pressures above some critical altitude but evaporates below that altitude. The control system has a valve which can delay the evaporation of the fluid by containing it in a pressure vessel; when released into a balloon the whole vehicle becomes positively buoyant and rises. Inertia causes it to overshoot the condensation altitude, and the fluid condenses more or less completely back into the bottle before the vehicle has lost so much buoyancy that it falls down through the critical altitude. Proper control of the valve allows the vehicle to stably oscillate about the critical altitude with an amplitude that can go as far as to touch or

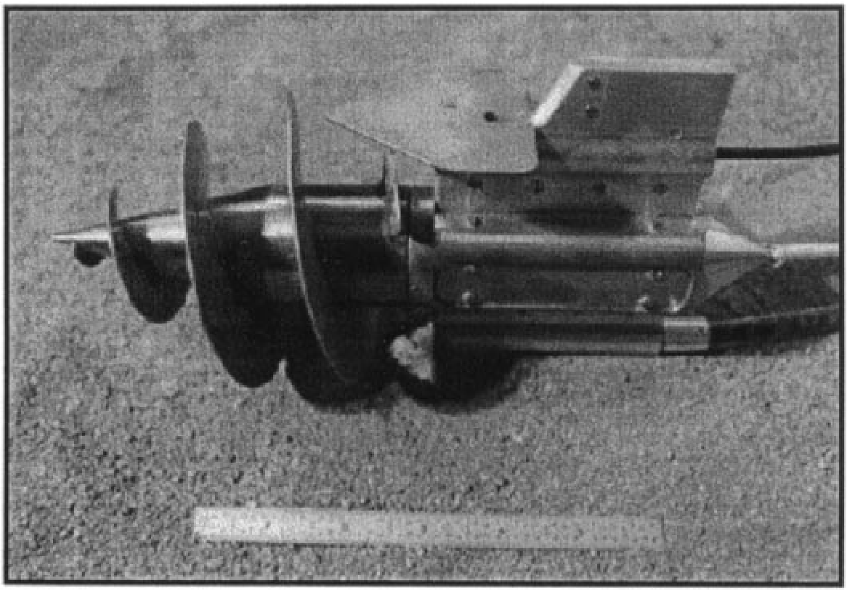

Figure 6. Subsurface explorer.

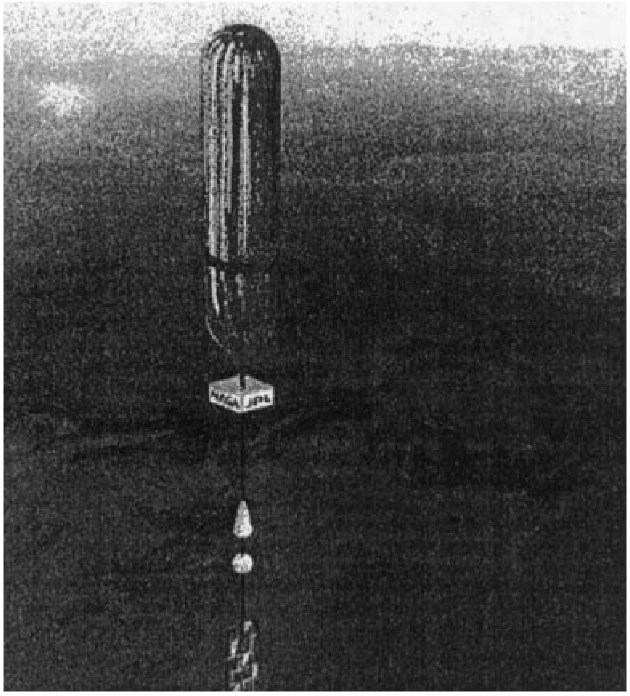

Figure 7. Artist's rendering of an aerobot, a flying robot, for exploring Venus.

land on the surface. Knowledge of the prevailing winds as a function of altitude might allow navigation to specific points on or over a planetary surface.

Material selection for mobile robots is very important. The overall mass of the vehicle determines the torque requirements of the motors, which in turn determine the size of the batteries or power system, which often then has a major impact on system mass and lifetime. This "chicken and egg" problem usually results in the mobility mechanism being some multiple often much greater than 1 times the payload, which includes the sensors and computer. The magnitude of this multiple is determined primarily by (1) the strength-to-weight ratio of the materials used in the chassis and (2) the performance of the actuators. This has driven mobile robot designers to use aluminum or fiber-composite frames and high-performance motors using Neodymium or Samarium magnets. JPL is also building an extremely light and compact chassis using three-dimensional composites (that is, with fibers running in all three directions so the superior material properties are roughly the same in all directions) and collapsible wheels.

CONTROL AND NAVIGATION

All mobile robots require some means for control and navigation. Control is the ability to power the actuators such that the vehicle moves stably in some desired way. Navigation is the ability to sense the environment so as to locate the vehicle with respect to goal points, hazards, other environmental features, or some absolute reference system. The navigation information is used to determine the desired path for the vehicle, which is then executed by the control system.

One of the most challenging applications of mobile robot control and navigation will be for future missions to the moon, Mars, or other planetary surfaces. Operation of these unmanned robotic vehicles with some form of human remote control is desirable to reduce the cost and increase the capability and reliability of many types of missions. However, the long time delays and relatively low bandwidths associated with radio communications between planets (due to the finite speed-of-light and the low power available for long-distance communications) precludes a "telepresence" approach to controlling the vehicle. For example, the round-trip speed-of-light delay between Earth and Mars varies from 6 min to 41 min, and typical data rates are only 10 kbit/s. At this data rate, it takes about 30 s to transmit a single compressed television-quality image. Thus it is impractical to have a rover that is teleoperated from Earth (that is, one in which every individual movement would be controlled through feedback from a human being). Therefore, some autonomy on the rover is needed. On the other hand, a highly autonomous rover (which could travel safely over long distances for many days in unfamiliar territory without any guidance from Earth regarding either navigation or science) is significantly beyond the present state of the art of artificial intelligence, even using computers vastly larger than those envisioned for deep space missions in the next few decades (which must be small, light, low-power, fault-tolerant, and radiation-hardened).

In between the two extremes just mentioned, various degrees of autonomy are possible. The Sojourner rover launched to Mars in December 1996 uses onboard behavior control to avoid hazards and to recover from certain failures, while using human waypoint designation for path and goal planning. Stereoscopic pictures from the lander or rover are sent to Earth, where they are viewed by a human operator using a stereoscopic display. The operator designates a path using a three-dimensional cursor, giving a safe path for the vehicle to follow leading to a science goal or as far as the operator feels he or she can comfortably go. Additional commands are included in a command queue to perform a time sequence of traverses, fine positioning with respect to rocks or other possible science targets, and science and engineering data gathering. This information is sent to the rover, which executes the sequence by dead reckoning (i.e., using odometry and inertial heading sensing). Hazards are sensed with a laser-striping/camera system which is able to measure the elevation of a two-dimensional array of points in front of the rover. If a hazardous terrain condition is detected, the rover will avoid it using simple behaviors. At the end of each command sequence (nominally once per day on the Sojourner mission), a new stereo pair of pictures is taken of the new position, and the whole process repeats. Depending on the terrain, the rover might travel about 5 m to 20 m for each of these command cycles. The Sojourner primary mission is within sight of its associated lander, which has a stereo camera on a mast some 1.4 m tall. This mast-mounted camera provides two important functions for the rover: the ability to see farther than the low-vantagepoint stereo cameras on the rover (which are only some 0.2 m above the terrain) and a permanent, fixed reference frame in which all the hazards, science targets, and other elements of the local environment can be localized.

For future longer-range rover missions, the rover will be guided by global routes planned on Earth using a topographic map which is obtained from images produced by a satellite orbiting Mars or from image sequences taken during the descent of the lander carrying the rover. These images would be used by a human operator (perhaps with computer assistance) to select mission objectives and an approximate corridor for the vehicle to follow, which avoids large obstacles, dangerous areas, and dead-end paths. Some form of topographic map for the corridor would be transmitted from Earth to the rover. The Long-Range Science Rover (LRSR) Rocky-7 at JPL uses a sun sensor for absolute (rather than inertial) heading sensing and has a long mast with a pair of stereo cameras so that it can perform the functions performed by the lander in the Sojourner mission.

The long-range rover views the local scene and computes a local topographic map by means of some sensor system such as stereo vision or laser scanning. This map will from time to time be matched to the local portion of the global map sent from Earth, as constrained by knowledge of the rover's current position from other navigation devices or previous positions, in order to determine the accurate rover position and to register the local map to the global map. This map is analyzed by computation on the rover to determine the safe areas over which to drive. A new path then is computed, revising the approximate path sent from Earth, since with the local high-resolution map small obstacles can be seen which might have been missed in the low-resolution pictures used on Earth. Using the revised path, the rover then drives ahead a short distance (perhaps a few meters), and the process repeats.

SENSING

All control and navigation approaches require some form of terrain sensing. As mentioned above, Sojourner uses a laser light-striping system to measure the elevations of a relatively coarse grid of points ahead of the rover. Passive vision, such as stereo correlation, requires no moving parts and has theoretical advantages in power consumption but suffers from the requirement for large amounts of computation. The current LRSR rover uses stereo correlation to perform the same elevation mapping functions at higher speed and with higher resolution than the Sojourner laser striping system. To accomplish this, it uses a processor whose performance is more than two orders of magnitude higher than that of the processor used by Sojourner, but still likely to be achievable within the constraints of next-generation flight computers and solar power budgets. Many mobile robots developed for terrestrial applications have used ultrasonic sensors for ranging due to their low cost and relative ease of integration. However, ultrasonic ranging sensors suffer from specularity (some observers have likened them to navigating through a darkened hall of mirrors with a flashlight taped on your head), poor angular resolution, and multiple echo returns. Internal sensing of the robot state is equally important. Included in this category are wheel odometry, heading sensing, acceleration or inclination sensing, and vehicle health sensors such as temperature or pressure sensors.

SUMMARY AND CONCLUSIONS

Mobile robots represent an enormous interdisciplinary systems challenge: to bring together mechanical, electrical, computer, sensing, control, and artificial intelligence expertise to make a complete system which accomplishes a useful function without an excessive reliance on human intervention. The rate of development in this field has been much slower than most predicted when research began in earnest in the 1960s and 1970s; people are now much better calibrated as to the difficulty of the problems and the complexity of the solutions. Fortunately, advances in computer technology have now enabled small mobile robots to have more computing capacity than once was reserved for vehicles remotely linked to huge, dedicated mainframe computers. As advances in computer miniaturization have allowed, for example, mobile robots to progress from laser scanning to stereo correlation for mapping the environment, future advances will allow ultraminiaturized machines to navigate effectively in complex environments and perform useful functions such as the scientific exploration of the various planets of the solar system.

BIBLIOGRAPHY

1. I. J. Cox and G. T. Wilfong (eds.), *Autonomous Robot Vehicles,* Berlin: Springer-Verlag, 1990.
2. S. S. Iyengar and A. Elfes (eds.), *Autonomous Mobile Robots,* New York: IEEE Press, 1991.
3. J. Jones and A. Flynn, *Mobile Robots: Inspiration to Implementation,* Wellesley, MA: A. K. Peters, 1993.
4. M. G. Bekker, *Theory of Land Locomotion,* Ann Arbor: Univ. of Michigan Press, 1957.

JAMES A. CUTTS
KERRY T. NOCK
JACK A. JONES
GUILLERMO RODRIGUEZ
J. BALARAM
BRIAN H. WILCOX
DAVID J. EISENMAN
California Institute of Technology