Mobile Robotics Research at Sandia National Laboratories

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Abstract

Sandia is a National Security Laboratory providing scientific and engineering solutions to meet national needs for both government and industry. As part of this mission, the Intelligent Systems and Robotics Center conducts research and development in robotics and intelligent machine technologies. An overview of Sandia's mobile robotics research is provided. Recent achievements and future directions in the areas of coordinated mobile manipulation, small smart machines, world modeling, and special application robots are presented.

Introduction

Sandia National Laboratories (SNL) is a multi-program national security laboratory operated by Sandia Corporation for the United States Department of Energy (DOE). Sandia has four primary mission objectives:

- Ensure that the U.S. nuclear weapons stockpile is safe, secure, and reliable and fully capable of supporting our nation's deterrence policy,
- Reduce the vulnerability of the United States to proliferation, use of weapons of mass destruction, and threats of nuclear incidents,
- Advance the surety (safety, security, and reliability) of critical global infrastructures, and
- Develop high-impact responses to emerging national security threats.

To meet these objectives Sandia employs a technical staff of nearly 4,000 engineers and scientists at sites in Albuquerque, NM, Livermore, CA, Tonopah Test Range, NV, and Kauai Test Facility, HW.

The DOE directs and sponsors robotics research and development efforts that lead to increased productivity, superior quality, improved safety, and enhanced security. A vision and commitment to develop intelligent systems for tasks too difficult or too dangerous for people led to the establishment of Sandia's Intelligent Systems and Robotics Center (IS&RC). The IS&RC has been designated by the DOE as a Center of Excellence for the Automation of Weapons Complex Reconfiguration. The myriad of technologies (Sandia 1996) under development at the IS&RC fall into three categories:

- Automated planning, programming, and navigation - The "brains" or reasoning for robots and intelligent systems.
- Sensor and model-based control - The "eyes" that accumulate and interpret data.
- Technologies of integration - The art of putting it all together, coordinating the hardware, software, and mechanical components that make a robotic system.

The over 100 scientists and engineers that make up the IS&RC are located in a recently completed 73,000 square foot robotics research facility shown in Figure 1, and at a 226 acre robotics test range shown in Figure 2.

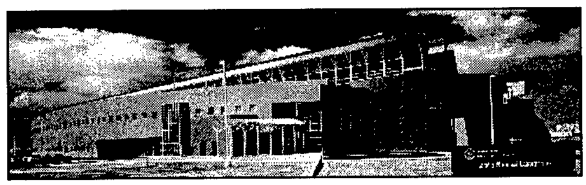

Figure 1. Sandia's Robotics and Manufacturing Science and Engineering Laboratory.

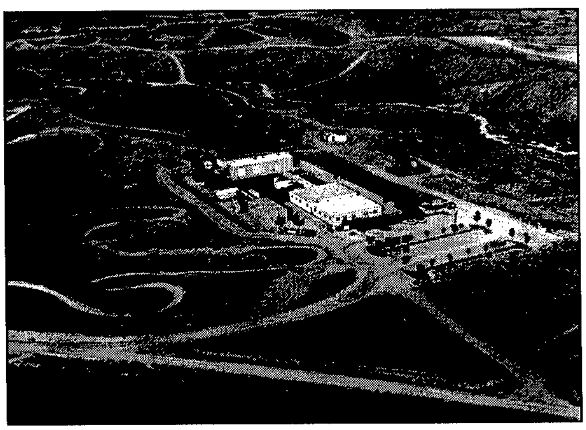

Figure 2. Sandia's Robotic Vehicle Range.

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DISCLAIMER

Mobile Robotics
Sandia has had an active mobile robotics program since 1984 developing over 40 mobile robotic systems for diverse application areas such as surveillance and reconnaissance, accident response, environmental sensing, weapons delivery, security monitoring and testing, and hazardous material handling. Figure 3 shows a family photo with several of Sandia's legacy robotic systems. Recent achievements and future directions in the areas of coordinated mobile manipulation, small smart machines, world modeling, and special application robots are presented in the following sections.

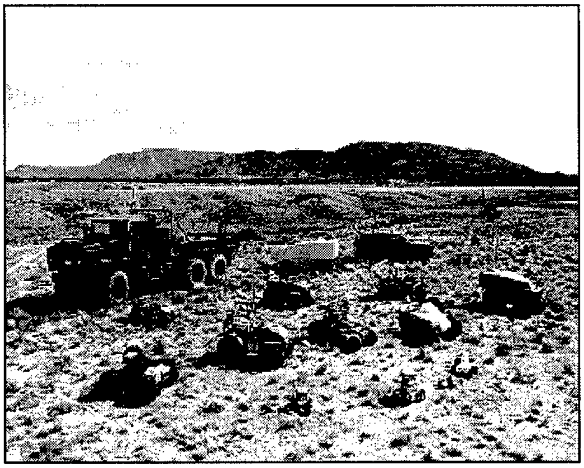

Figure 3. Mobile Robots Family Portrait

Coordinated Mobile Manipulation
Many complex hazardous tasks that occur in the field require dexterous manipulation, e.g., the removal of a bomb fuse, the use of a cutting torch, the closing of a fuel supply valve, the removal of contaminated debris, and so on. To accomplish these tasks, robotic manipulator development efforts in environmental and weapon related programs are continuing to be leveraged into Sandia mobile robotic systems. One example of this is the REmote TeleRobotic Vehicle for Intellegent Remediation (RETRVIR) shown in Figure 4. RETRVIR has been successfully used to extend and develop complementary robotic technologies such as model based path planing and sensing for collision avoidance, automated in-field structure assembly, and machine vision object cueing and targeting. Building on RETRVIR's experience and capabilities is the Accident Response Mobile Manipulation System (ARMMS) (Morse et al. 1994) shown in Figure 5. Coordinated multiple manipulation is currently being instituted as part of ARMMS to enhance its capabilities for responding to accidents that may involve nuclear materials. This cooperative manipulation will be extended to include simultaneous mobility which will enable tasks not previously possible, e.g., lifting and pushing a wall assembly up to a vertical position, grabbing and dragging a human from harms way, and so on. Long term development goals include the realization of multiple manipulator based mobile robots cooperatively accomplishing complex tasks such as the automated assembly of a containment structure at an accident site.

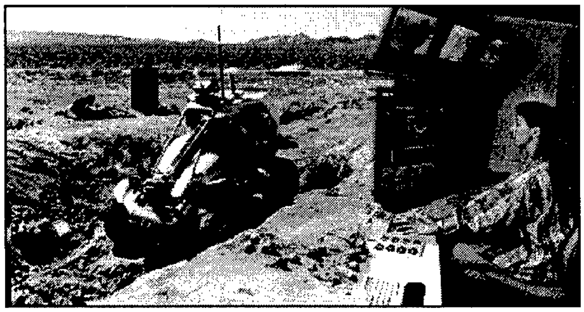

Figure 4. The REmote TeleRobotic Vehicle for Intelligent Remediation (RETRVIR) is shown depositing an uncharacterized object from Sandia's explosive test site with the operator's graphical planning and programming interface shown on the right.

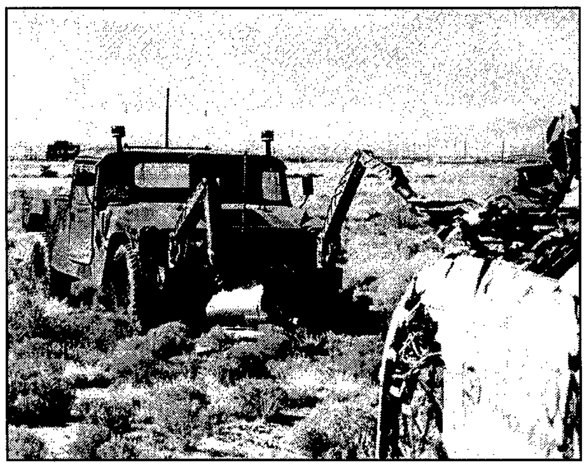

Figure 5. The Accident Response Mobile Manipulation System (ARMMS) at a simulated aircraft crash site involving nuclear materials.

Facilitating these developments has been the patented (Anderson 1996c) Sequential Modular Architecture for Robotics and Teleoperation (SMART). SMART is a modular software control architecture that enables the graphical creation and programming of robot behaviors for arbitrary combinations of multiple robot types, input devices, sensors, constraints, kinematics, and dynamic filters

(Anderson 1996b). SMART's underlying control theory maintains and guarantees the stability (Anderson 1996a) of these arbitrary robotic systems. Its scalable design allows the system to evolve and rapidly integrate new technologies. Quick adaptation to changing mission needs by prompt in-the-field reconfiguration of robotic system hardware and behavior is another capability provided by SMART. SMART's Visualizer and GUI Editor for building systems are shown Figure 6. SMART has been successfully demonstrated and used to control and coordinate up to four heterogeneous fixed mounted six and seven degree of freedom robotic manipulators. It has also been successfully deployed as part of DOE's Hanford tank characterization and remediation efforts as well as part of a NAVY robotic painting demonstration program. SMART modules are currently being extended and built for a wide class of vehicular robots.

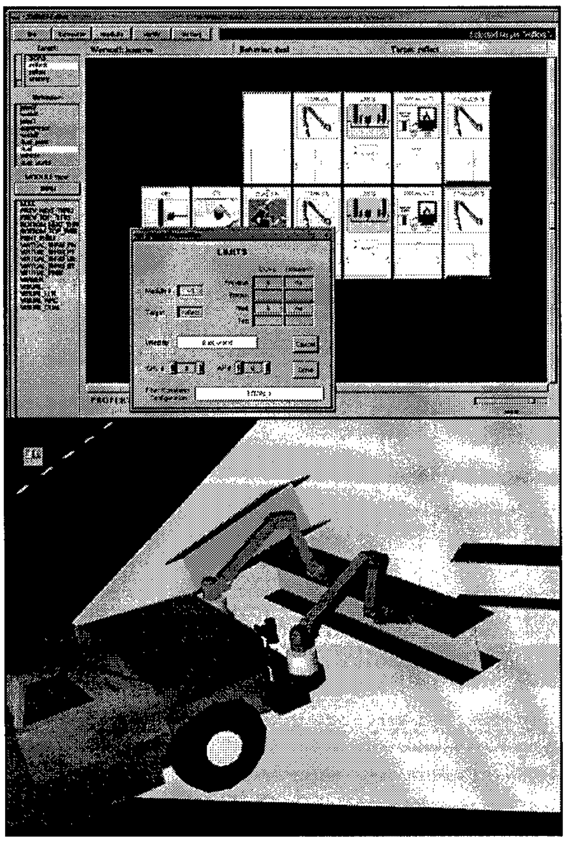

Figure 6. Sequential Modular Architecture for Teleoperation and Robotics (SMART) development environment. Shown on top is the SMART GUI Editor and below is the system Visualizer.

Small Smart Machines

Small Smart Machines (SSM) are intelligent devices capable of performing a wide variety of tasks, e.g., surveillance and inspection, searching, following, tagging, locating and identifying targets, and deploying and manipulating objects. SSM have capabilities, as required, for mobility, manipulation, stealth, communications, sensing, navigation, signal processing and cooperative behaviors. SSM, as we define them, are less than 1 cubic foot in volume and characteristically are inexpensive to manufacturer.

As SSM evolve toward smaller and smaller dimensions, significant technological challenges arise in mobility, communications, navigation, sensors, power, and intelligence processing. To establish a baseline with current commercial off-the-shelf components, a 1 inch cubed, wire guided autonomous robot, MARV, shown in Figure 7, was developed. Meso and micro scale robots face unique mobility challenges that wheeled systems such as MARV will not be able to overcome. Hopping systems, morphological self-assembly, parasitic transportation, and other unique mobility mechanisms are being explored to address these difficult issues.

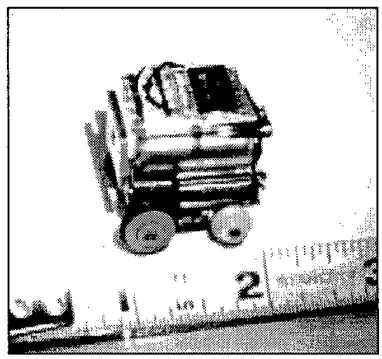

Figure 7. The Mobile Autonomous Robotic Vehicle (MARV) is a one inch cubed wheeled vehicle capable of tracking a 96KHz signal in a buried wire. MARV contains two Micromo motors, two N Cell batteries, a PIC microcontroller, and a Sandia-developed capacitance sensor for signal strength measurement.

Advances in MicroElectroMechanical Systems (MEMS) will help accelerate the realization of mesosocopic and microscopic robots by providing new and novel devices for power, sensors, communications, and processing (Smith 1996). Microsteam engines and gear trains, similar to those shown in Figures 8 and 9, might provide necessary power and propulsion systems for very small robotic vehicles. Hybrid inertial navigation systems (Bruder and Pletta 1997) evolving from recent MEMS three axis accelerometer developments (Lemkin et al. 1997), shown in Figure 10, may soon be possible. Chemical sensing by placing a chemistry lab on a chip, as shown in Figure 11, will be demonstrated

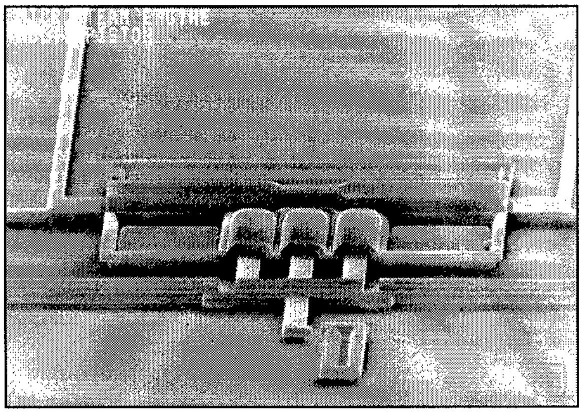

Figure 8. A three-cylinder microsteam engine is shown. Water is heated inside of the cylinders using electric current to stroke the piston rods out. Upon removal of the electric current capillary forces retract the piston.

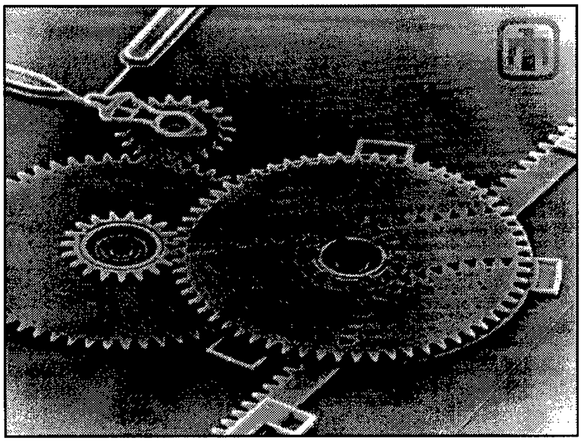

Figure 9. Shown driving this reduction (9.6 to 1) gear set is an electrostatic microengine. The gear train drives a rack and pinion slider

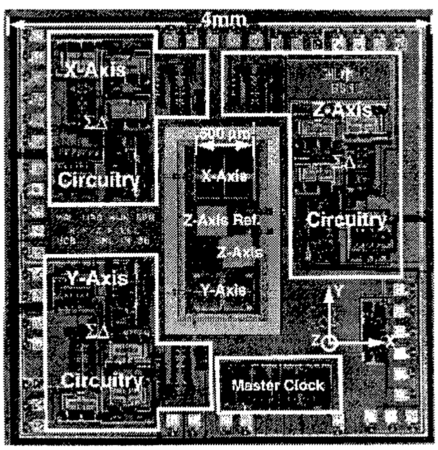

Figure 10. Three-axis accelerometer system-on-a-chip based upon a U.C. Berkeley design.

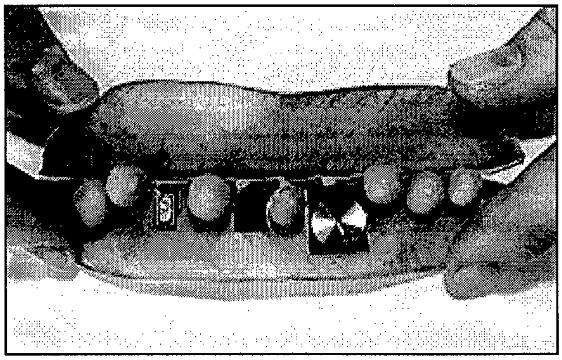

Figure 11. Chemistry lab-on-a-chip devices shown inside of a pea pod for size contrast. The first component on the left is a surface acoustic wave sensor array, then a preconcentrator, and lastly a chromatograph column.

using multiple mobile robots to cooperatively seek and locate chemical sources.

Mathematical formulations for cooperative control are being developed and used to design behaviors that focus on collectively achieving a designated goal within prescribed levels of certainty. Sandia has developed and applied several successful decentralized control techniques that are provably stable with predictable convergence characteristics to guide multiple robots to a goal (Feddema, Robinett, et al. 1997; Kwok and Driessen 1997). Most of these techniques are based on optimization methods where the distance to the goal is minimized, creating an attractive force, or maximized, creating a repulsive force. These control schemes have recently been demonstrated, under DARPA funding, on four Swarm-Size Robotic All Terrain Lunar Exploration Rovers (RATLER) to establish a robotic security perimeter by a single warfighter as shown in Figure 12. For vehicles with less computational power, a simplified Fuzzy controller has been developed based on a Linear Quadratic Regulator (LQR) design (Driessen et al. 1998) that is easily implemented on a simple 8-bit microcontroller such as in the mesoscopic pen-shaped robot shown in Figure 13. Beyond classical control methods, approaches such as genetic programming, continuum analogies, and statistical mechanics models are being explored to further develop control strategies capable of predictable, repeatable behavior within large swarms of cooperative robotic agents.

A Sandia simulation and development tool has been created to model the state of multi-robotic systems: robot positions and orientations, sensor configurations and data, and a 2-D sensor-based map of identified obstacles and targets in the environment. The simulator is an effective tool used to evaluate

Figure 12. Robotic Security Perimeter system consisting of four Swarm-Size Robotic All Terrain Lunar Exploration Rovers (RATLER), Mobile Intrusion Detection Sensors (magnetometers, sesmic, passive and active IR), a laptop base station with data and video radios.

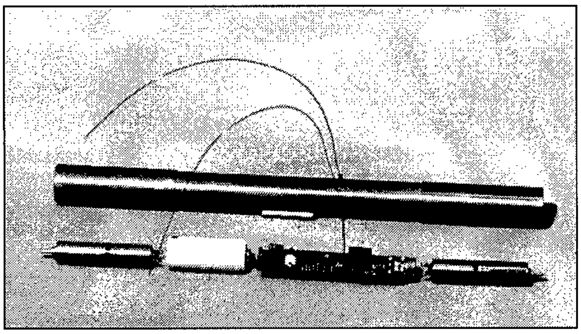

Figure 13. This Mesocopic pen shaped robot uses an Analog Devices MEMS accelerometer to detect and drive toward seismic sources. The robot is 18 cm long and contains two electric motors, battery, RF transmitter, and electronics.

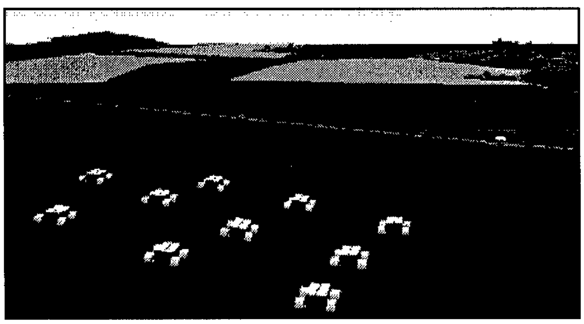

Figure 14. Sandia simulation system shows a small swarm of cooperative RATLERs moving in formation.

robot control algorithms as well as robot designs (specifically, the sensor suites). An example of the simulator graphical display is shown in Figure 14.

World Modeling

Rapid world modeling is an enabling technology that allows robots to navigate and manipulate safely and efficiently within unknown and highly unstructured environments. Missions such as accident and emergency response, surveillance and reconnaissance in urban terrain, disabling improvised explosive devices, and so on, will be greatly enhanced by rapid world modeling capabilities.

One world modeling approach under development is the LAser MApper (LAMA) system that can sense objects and build 3-D computer models using structured laser lighting (Little and Wilson 1996; Feddema and Little 1997). The LAMA system utilizes a single camera and a plane of laser light to create 3-D computer models. This technique eliminates image correlation problems associated with stereo cameras. Model building begins with connecting range data points into a surface, and includes filtering to increase robustness, and data reduction to end up with usable model data sizes. Figure 15 shows a LAMA created world model with a partially buried barrel believed to contain hazardous materials. The world model, created in approximately 6 minutes, enables the graphical planning, programming, and simulation (McDonald and Palmquist 1993) of a robot taking a swipe survey along the barrel's dented region. Upon successful testing in a virtual world, the operation can then be executed in the real world under high-level supervisory control. LAMA has also been successfully implemented as part of a mobile robotic platform to perform interior building mapping (Barry et al. 1995; Barry et al. 1997a, 1997b).

Another promising sensor under investigation is the Scannerless Range Imager (SRI) technology patented by Sandia (Scott 1990). The SRI utilizes modulated laser floodlight illumination, gain modulated image intensified CCD cameras, and unique digital image processing methods to create 3-D range imaging as shown in Figure 16. The present system has an intermediate resolution of a fraction of a meter. It is anticipated that new components and image processing methods under development will enable an order of magnitude improvement of spatial resolution in the near term.

Stereo imaging has also been successfully used to perform visual targeting to locate objects in space (Wilson and Selleck 1994). Two arbitrary cameras are used to present two video perspectives of a scene. An operator identifies the location of corresponding features in each image. The position and orientation of the cameras, the geometry of the calibrated camera models, and the corresponding image locations are all used to determine the 3-D location of the feature in

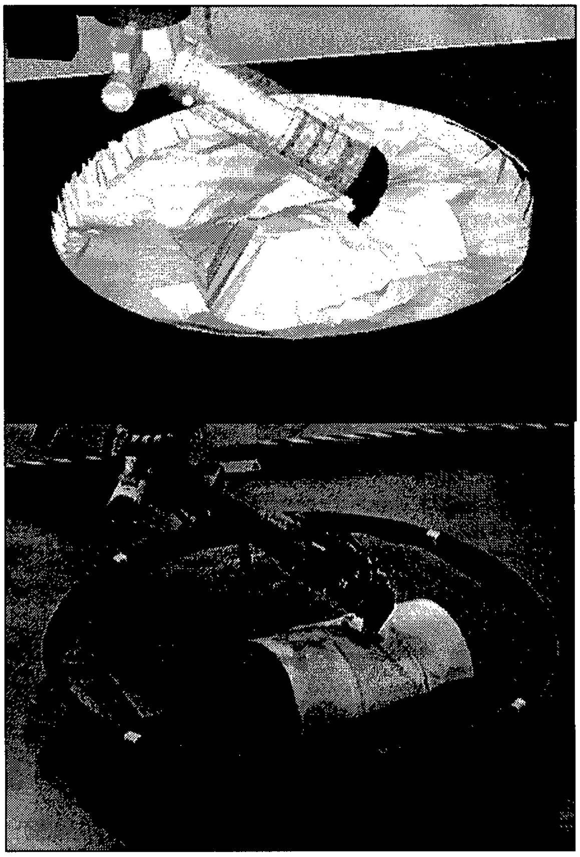

Figure 15. The top image shows a LAMA created world model interacting with a robot in the virtual world. The lower image shows the graphically programmed task executing in the real world.

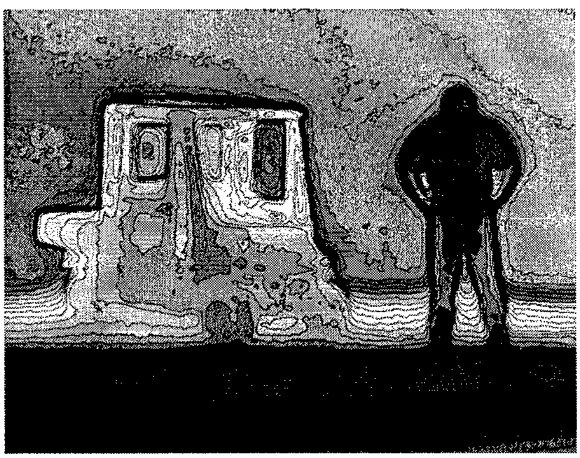

Figure 16. Scannerless Range Imager (SRI) showing range information from an electric cart and human.

space. Multiple target points can be combined to define the extent and orientation of an object, or the position and orientation of a grasp point. This capability enables high-level supervisory control by

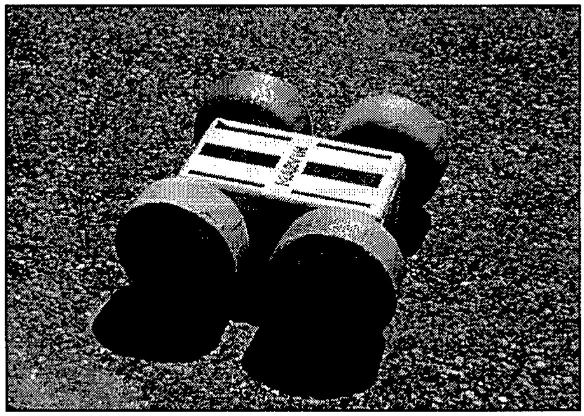

Figure 17. Marvin has been designed for unique high shock deployment requirements.

simply designating goals on a video scene for both manipulation and driving tasks.

Special Applications

Situations arise that require the service of specialized mission robots. These robotic systems may: provide rapid proof of concepts and technologies, have short operational life spans (including one-time-use), require special security measures, and have significant consequences associated with their operation. Five representative samples of these types of systems are given:

1. Marvin – This robot is being developed under internal R&D money to explore air delivery of ground vehicle systems. Marvin, shown in Figure 17, is a RATLER derivative that will be capable of being dropped from a height of 10 ft. at 50 mph and then be teleoperable to a location one mile from the drop point.
2. Satellite Teleoperation - A secure satellite data link for telerobotic operation has been successfully demonstrated.
3. Nuclear Material Inspection Robot – A prototype robot shown in Figure 18 that can be remotely used by International Atomic Energy Agency inspectors to conduct remote inspections is being demonstrated.
4. Nuclear Material Handling – An automated lift truck shown in Figure 19 has been adapted and enhanced to provide necessary levels of safety as well as the capability to conduct inventories and confirmation measurements.
5. Demilitarization – Small lot disassembly of explosive devices such as nuclear weapon gas generators and other ordnance is accomplished using specialized robotics as shown in Figure 20. This technology is being studied for extension to mobile applications.

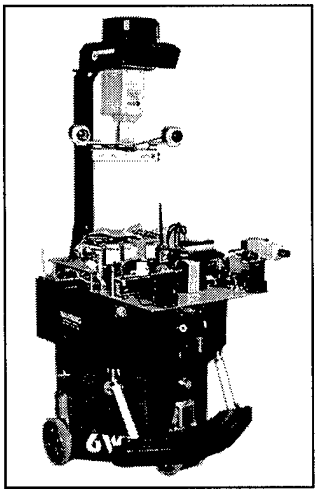

Figure 18. A robotic system used for remote nuclear material Inspections.

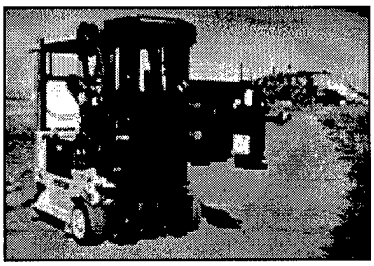

Figure 19. An automated lift truck used to store, retrieve, and inspect nuclear materials.

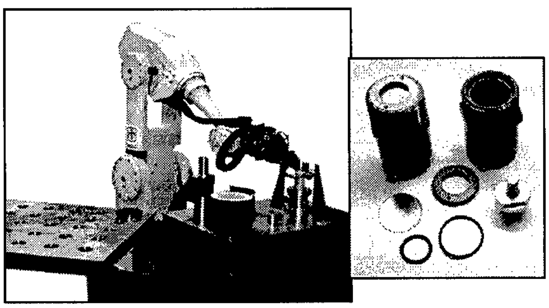

Figure 20. An automated explosive gas generator disassembly robot with the component parts of the MC1362 shown on the right.

Conclusion

Sandia's IS&RC has developed and is advancing a broad range of technologies applied to mobile robotic systems. IS&RC is committed to developing mobile robotic systems for tasks that are too difficult or too dangerous for people.

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