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UGV HISTORY 101:
A Brief History of
Unmanned Ground Vehicle (UGV) Development Efforts

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"Those who cannot remember the past are condemned to repeat it" -- George Santayana

INTRODUCTION

The purpose of this paper is to provide a brief survey of a number of different threads of development that have brought the UGV field to its current state, together with references to allow the interested reader to probe more deeply.

In the broadest "dictionary" sense, an *unmanned ground vehicle* (UGV) is any piece of mechanized equipment that moves across the surface of the ground and serves as a means of carrying or transporting something, but explicitly does NOT carry a human being. A discussion of such a broad universe of possible UGV systems needs some organizing principle, and in fact a taxonomy of UGV systems could be based upon any of a number of characteristics of each system, including:

• the purpose of the development effort (often, but not always, the performance of some application-specific mission);

• the specific reasons for choosing a UGV solution for the application (e.g., hazardous environment, strength or endurance requirements, size limitation);

• the "long pole" technological challenges, in terms of functionality, performance, or cost, posed by the application;

• the system's intended operating area (e.g., indoor evironments, anywhere indoors, outdoors on roads, general cross-country terrain, the deep seafloor, etc.);

• the vehicle's mode of locomotion (e.g., wheels, tracks, or legs);

• how the vehicle's path is determined (i.e., control and navigation techniques employed).

To reasonably limit its scope, this survey will focus principally on the large number of systems where the "long pole" technological challenge is or has been in the area of navigation and control. Within that context, a *teleoperated* vehicle system is one in which navigational guidance is transmitted to the vehicle from an externally situated human operator; an *autonomous* vehicle is one which determines its own course using onboard sensor and processing resources; the name *supervisory control* is often given to the myriad of control schemes which combine inputs from both an external human operator and onboard sensors to detemine the path. We will not discuss *Automated Guided Vehicles*, or *AGVs* [Rajaram, 1988] -- those vehicles whose path of motion is *physically predetermined* (either mechanically constrained, as by rails, or inflexibly following some pre-marked path. Furthermore, we will merely mention in passing a number of very interesting systems which involve other dominating technological issues, such as legged locomotion or manipulation.

MACHINES WITH LEGS

Since humans and other animals can easily walk over terrain too rough for any wheeled vehicle to traverse, machines that use legs to walk have long held a special fascination for inventors. The mechanically inclined have introduced marvelous mechanisms to move legs in a desired gait, but this basic strategy does not afford the adaptibility to terrain that animals display. Artificial intelligence researchers devise clever strategies for planning the placement of each footstep on uneven terrain, creating four-legged machines that run and even one-legged machines that hop. Some biologists catalog animal gaits, while others devise electronic models of a cockroach's walking circuit comprising only a few dozen neurons -- and validate the scheme by controlling the walking of a small legged testbed. Major achievements have included the ARPA-funded Ohio State University *Adaptive Suspension Vehicle (ASV)*, which is a manned vehicle [McGhee, 1985] and CMU's highly specialized *Dante* walkers [Asker, 1994] funded by NASA, which have ventured to explore volcanoes in Antartica and Alaska.

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Considerations of energy and complexity suggest that general purpose walking machines will only be successfully employed in an application when other simpler and cheaper approaches have been found wanting. From a management perspective, one problem is that researchers who undertake to develop a walking robot often focus most of their attention and resources on the mechanics, dynamics, and control of walking, rather than achieving a fully capable integrated system. Before you can make a robot walk, you've got to make a robot.

MACHINES WITH TOOLS

A number of applications call for machines that can move to a desired area and then perform some sort of work involving manipulation or using any of a variety of tools ("effectors" is the robotic terminology). The issues involved in performing manipulation or other work without a human present often dominate over the UGV navigation and control issues, and tend to be application-specific. Application domains addressed by continuing major development efforts include:

- The nuclear industry, doing work in areas with radiation levels dangerous to human workers. The Center for Engineering Systems Advanced Research (CESAR) at Oak Ridge National Laboratory (ORNL) is a major hub for DOE-funded work, including the *HERMIES* series of mobile robots.

- Military heavy equipment for moving dirt under enemy fire, such as repairing craters in a runway or breaching a minefield or other barrier. The Air Force has the lead in this area with projects such as *Rapid Runway Repair*.

- Strong manipulators for moving and loading heavy items such as ammunition. Army Human Engineering Lab (HEL) efforts have included the *Soldier-Robot Interface Program (SRIP)* and the *Field Material Handling Robot Technology (FMR-T)* project.

- Explosive ordnance disposal (EOD) -- manipulators capable of dealing with packages containing suspected bombs, unexploded ordnance, etc. The Navy's EODTECHDIV has the joint services lead in this area; one project has been the *Robotic Ordnance Neutralizing Device (ROND)*.

As an aside, systems incorporating both mobility and manipulation are certainly not limited to UGVs. For example, NASA's *Flight Telerobotic Servicer (FTS)* was intended to support space station construction, and the proliferation of "subsea completions" at ever increasing depths in the offshore oil industry has stimulated the continuing development of UUVs capable of heavy work. NRaD's *TeleOperator /telePresence System (TOPS)* development addressed the key issues involved in remotely performing tasks requiring human-level dexterity and judgment [Shimamoto, 1992].

We turn now to our principal focus of UGV systems whose "long pole" technological challenge is or has been in the area of navigation and control. Following a survey of some early research efforts, we trace several threads of program sponsorship and associated "communities of interest," plus several other interrelated threads of ongoing development efforts addressing specific application domains

EARLY RESEARCH EFFORTS

The academic community usually refers to UGVs (especially UGVs possessing significant autonomous capabilities) as *mobile robots*. There is a certain irony in this terminology, since many of the key research issues (e.g., "inverse kinematics") addressed in "traditional" robotics (oriented to the control of industrial manipulators) are completely irrelevant to mobile robots. There is some commonality in issues relating to path planning, obstacle avoidance, and sensor-based control, but results have tended to flow more from mobile robots to manipulators, rather than in the other direction. The focus of mobile robotic research has in fact evolved from the discipline of artificial intelligence (AI). Surveys of early mobile robots and autonomous vehicle research include [Flynn, 1985], [Harmon, 1986], [Klafter, 1988], [Meystel, 1991], [Everett, 1995].

The first major mobile robot development effort was *Shakey*, developed in the late 1960s to serve as a testbed for DARPA-funded AI work at Stanford Research Institute (SRI) [Nilsson, 1969]. Shakey was a wheeled platform equipped with steerable TV camera, ultrasonic range finder, and touch sensors, connected via an RF link to its SDS-940 mainframe computer that performed navigation and exploration tasks. As befit an AI testbed, the Shakey system could accept English sentence commands from the terminal operator, directing the robot to push large wooden blocks around in its lab environment "world". While Shakey was considered a failure in its day because it never achieved autonomous operation, the project established functional and performance baselines for mobile robots, identified technological deficiencies, and helped to define the AI research agenda in such areas as planning, vision, and natural language processing [Flynn, 1985].

From 1973 to 1981, Hans Moravec led the *Stanford Cart* project at the Stanford University AI Lab, exploring navigation and obstacle avoidance issues using a sophisticated stereo vision system [Moravec, 1983] The Cart's single TV camera was moved to each of 9 different positions atop its simple mobility base, and the resulting images were processed by the offboard KL-10 mainframe. Feature extraction and correlation between images allowed reconstruction of a model of the 3-D scene, which was used to plan an obstacle-free path to the destination. The system was incredibly slow, taking up to 15 minutes to make each one-meter move. Moravec moved to Carnegie Mellon University (CMU) in 1981 and continued his work on the smaller *CMU Rover* [Moravec, 1983] indoor platform. CMU became a major leader in mobile robot research during the 1980s, with its *Navlab* vehicle as the focus for much of the work [Thorpe, 1990].

A number of other research-oriented mobile robot development efforts (e.g., the French *HILARE* project [Giralt, 1983]) that were undertaken in the late 1970s and early 1980s are described in [Klafter, 1988]; various application-focused developments are described in appropriate sections below.

DARPA AUTONOMOUS LAND VEHICLE (ALV)

The ARPA-sponsored development thread of "mobile robots as an application domain for the demonstration of AI and high performance computing techniques" that was begun in the late 1960s with Shakey reemerged in the early1980s as the DARPA *Autonomous Land Vehicle (ALV)*. Under DARPA's Strategic Computing (SC) Program, the ALV served as one of several applications projects whose goal was to "provide a realistic task environment for technology research". Other SC applications included Naval Fleet Command Center Battle Management (FCCBMP), Army Air Land Battle Management (ALBM) and a "Pilot's Associate". [DARPA, 1986]

The ALV was built on a Standard Manufacturing eight-wheel hydrostatically-driven all-terrain vehicle capable of speeds of up to 45 mph on the highway and up to 18 mph on rough terrain. The ALV could carry six full racks of electronic equipment in dust-free air conditioned comfort, providing power from its 12-kW diesel APU. The initial sensor suite consisted of a color video camera and a laser scanner from the Environmental Research Institute of Michigan (ERIM) that returned a 64 by 256 pixel range image at 1-2 second intervals [Everett, 1995]. Video and range data processing modules produced road-edge information that was used to generate a model of the scene ahead. Higher level reasoning was performed by goal-seeker and navigator modules, which then passed the desired path to the pilot module that actually steered the vehicle. The integration contractor for the ALV project, Martin-Marietta, incorporated functional components provided by a number of other ARPA-funded technology developers, including Hughes Research Lab, Carnegie-Mellon University, and University of Maryland [Martin Marietta, 1986].

ALV road-following demonstrations began in 1985 at 3 km/h over a 1-km straight road, then improved in 1986 to 10 km/h over a 4.5-km road with sharp curves and varying pavement types, and in 1987 to an average 14.5 km/h (max 21 km/h) over a 4.5 km course through varying pavement types, road widths, and shadows, while avoiding obstacles. Also in 1987, vision-guided off-road transit was demonstrated along a 0.6-km course at speeds up to 3 km/h over rolling terrain while avoiding ditches, rocks, trees, and other small obstacles. The ALV Program's focus was moved in early 1988 away from integrated demonstrations of military applications and toward the support of specific scientific experiments for off-road navigation. [Douglass, 1988]

The US Army Tank-Automotive Command (TACOM) / DARPA *Advanced Ground Vehicle Technology (AGVT)* program adapted navigational techniques developed under the ALV program to vehicles military more suited to military applications. Parallel contracts were awarded to General Dynamics Land Systems Divison [Davies, 1990] and FMC Corporation [Sharma, 1987], and AGVT demonstrations were held at Martin Marietta's ALV test track in Colorado and at Fort Knox in 1987.

RECONNAISSANCE, SURVEILLANCE, AND TARGET ACQUISITION (RSTA)

The Reconnaissance, Surveillance, and Target Acquisition (RSTA) application has long drawn the attention of UGV developers, since a UGV solution for RSTA would provide a battlefield commander with a direct sensing capability on the battlefield and even behind enemy lines, without endangering human personnel. Two RSTA-oriented UGV projects were undertaken at the Naval Ocean Systems Center (NOSC) in the early 1980s under the auspices of the US Marine Corps' Exploratory Development (6.2) Surveillance Program: the *Ground Surveillance Robot (GSR)* at NOSC San Diego, and the Advanced Teleoperator Technology (ATT) *TeleOperated Dune Buggy* at NOSC Hawaii. NOSC was later renamed the Naval Command Control and Ocean Surveillance Center, Research Development Test and Evaluation Division -- NCCOSC RDTE DIV, or NRaD for short. A third element of this 6.2 program was the *Airborne Remotely Operated Device (AROD)*, a small ducted-fan UAV whose successor, the *Air-Mobile Ground Security Surveillance System (AMGSSS)*, is a ducted-fan vehicle deployed for ground-based RSTA [Murphy, 1995].

The GSR project explored the development of a modular, flexible distributed architecture for the integration and control of complex robotic systems, using a fully actuated 7-ton M-114 armored personnel carrier as the testbed host vehicle. With an array of fixed and steerable ultrasonic sensors and a distributed blackboard architecture implemented on multiple PCs, the vehicle successfully demonstrated autonomous following of both a lead vehicle and a walking human in 1986 before funding limitations terminated its development [Harmon, 1987].

The ATT teleoperated dune buggy, on the other hand, concentrated exclusively on teleoperator control methodology and on "advanced, spatially-correspondent multi-sensory human/machine interfaces." With a Chenowth dune buggy as a testbed vehicle, the ATT project successfully demonstrated the feasibility of utilizing a remotely operated ground vehicle to transit complex natural terrain and of remotely operating vehicle-mounted weapons systems. In addition, the ATT effort demonstrated the efficacy of stereo head-coupled visual display systems, binaural audio feedback, and isomorphic vehicle controls for high-speed remote vehicle operations. [Hightower, 1986]

The success of the ATT and GSR vehicles led the Office of the Undersecretary of Defense for Tactical Warfare Programs/Land Warfare (OUSD/TWP/LW) in 1985 to initiate the Ground/Air TeleRobotic Systems (GATERS) program, under Marine Corps management and with NOSC serving as the developing laboratory. The thrust of the GATERS program was to develop a *TeleOperated Vehicle (TOV)* to support the test and evaluation of UGV product concepts by prospective military users of UGVs. The TOV system consisted of a remote vehicle and an operator control station, connected by fiber optic cable to provide high bandwidth secure non-line-of-sight communications for distances up to 30 km. The TOV remote vehicle was a HMMWV, and up to three TOV control stations were housed in a shelter mounted on the back of another HMMWV. Building on the dune buggy experience, the TOV operator was provided with stereo head-coupled visual displays, binaural audio, and driving controls isomorphic to those found in an actual HMMWV. A RSTA package (video and FLIR cameras and an active laser rangefinder/ designator) was mounted on a pan/tilt unit atop a scissors lift that could be raised up to 15 feet off the ground. A high level control architecture was implemented to integrate the functionality of the system. Successful demonstrations of the TOV began at Camp Pendleton in May 1988, including long range RSTA, high-speed cross-country transit, detection of chemical agents, and remote firing of a 50-caliber machine gun. [Aviles, 1990].

Meanwhile, as early as 1982, the Army's Missile Command (MICOM) began investigating possible robotic systems for battlefield use. The initial focus was on remotely activated anti-armor weapons, allowing a soldier to fire a shoulder-mounted missile at a tank without having to actually carry it on his shoulder. The first prototype of the Grumman *Robotic Ranger* was fabricated in 1984, and demonstrated remote missile firing. In 1985, remote missile and machine gun firings were demonstrated from the RDS *PROWLER*(described below in the section on security robots).

These successful demonstrations led to the formulation of the *Teleoperated Mobile Anti-Armor Platform (TMAP)* program, and prototype systems were procured in 1987/1988 from Grumman and Martin Marietta. Both systems were joystick-controlled via fiber optic link, the operator navigating via the returned TV image. The Grumman system was a hybrid diesel-electric drive with its four wheels in an articulated diamond pattern, while the Martin vehicle was a diesel-powered hydrostatic four-wheel drive with skid steering (a detailed description of the Martin system is provided in [Weiss, 1988].) Unfortunately, Congressional direction in December 1987 prohibited the emplacement of weapons systems on robots, and the TMAP was retargeted to the RSTA mission and renamed the *Teleoperated Mobile All-Purpose Platform*. [Young, 1990]

As the culmination of a joint Army/Marine Corps Advanced Technology Demonstration project, a demonstration incorporating both the Army's TMAPs and the GATERS TOV was held at Camp Pendleton in September 1989, featuring a live-fire scenario in which the TOV and TMAP designated targets for laser-guided Hellfire missiles and Copperhead rounds.

UNMANNED GROUND VEHICLES/ SYSTEMS JOINT PROGRAM OFFICE (UGV/S JPO)

Concerned by a proliferation of apparently uncoordinated UGV development efforts, Congress mandated as part of the Defense Appropriations bill for FY-1990 that all ground vehicle robotics projects within DoD be consolidated under the policy and program direction of the Office of the Secretary of Defense. The Unmanned Ground Vehicles Joint Program Office (UGV JPO) was formed as the central focal point for the development and fielding of DoD UGV systems. The word "Systems" was later added to the program office name, so the organization is now the UGV/S JPO. The principal effort of OSD and the JPO is the development and fielding of the *Tactical Unmanned Ground Vehicle*, or *TUGV*. Toward this end, a Memorandum of Understanding between the Army and Marine Corps was established in 1990, and the program has since progressed through many of the numerous wickets of the formal acquisition process. [Toscano, 1992], [Hall, 1992], [UGV/S JPO, 1995]

A key element of the TUGV development strategy has been the near-term fielding of testbed vehicles to allow users to develop and refine UGV operational concepts. To support this, the *Surrogate Teleoperated Vehicle (STV)* program was initiated in 1990. Developed by Robotics Systems Technology (RST) under contract to NRaD (formerly NOSC), the STV was designed to be small enough to be helicopter- and HMMWV-transportable, but large enough to accommodate a human driver and fast enough to keep up with a tactical vehicle convoy (35 mph). The STV is built on a six-wheel all terrain vehicle from Polaris Industries, featuring 25-hp diesel engine (with "quiet" electric backup) and Ackerman steering. The operator drives the vehicle using stereo TV imagery (head-mounted display optional) via either RF or fiber optic cable datalink, and the vehicle carries a GPS receiver to help the operator navigate. The RSTA mission module contains stereo TV (color for daytime and image intensified black and white for night), FLIR imager, laser rangefinder/ designator, chemical weapons detector, and acoustic detection system, mounted on a pan/tilt unit atop a scissors lift. The first of the 14

STV vehicles produced was fielded for the first time with a group of soldiers and marines in a Concept of Employment Exercise (COEE) at Fort Hunter-Liggett CA in February and March of 1992. While the STV demonstrated that it could maneuver well in heavily wooded areas and on muddy slopes, it could not traverse deep ditches; moreover, the RSTA payload used the full capacity of the platform, limiting future flexibility. Moreover, it was confirmed that "remote presence" visual displays such as stereo vision and pitch and roll icons permit driving at higher speeds and on steeper side slopes by providing the operator with an enhanced sense of spatial and geographic awareness. [Metz, 1992]

The UGV/S JPO has three additional vehicles under development in support of the TUGV program:

- The*Surveillance and Reconnaissance Ground Equipment (SARGE)* is intended to put eight units of prototype hardware into the hands of prospective users to conduct operational appraisals while using the systems in their day-to-day operations. Hopefully, this will create a sense of ownership among the user community, as well as provide constructive feedback to the developers. SARGE is an upgrade of the *Dixie* vehicle developed by Sandia National Laboratory.

- The *Technology Test-Bed (TTB)* is a system being developed by MICOM RDEC using components and technology developed or procured for the TOV and STV systems. Built on a HMMWV, the TTB will serve to support the evaluation of various systems architectural concepts and candidate component technologies.

- The *GECKO* program is intended to support the evaluation of a supervisory-level vehicle driving scheme called Feedback Limited Control System (*FELICS*). In this scheme, similar in concept to JPL's CARD system (described below under planetary rovers), the operator marks the desired driving path on the driving display screen and the vehicle then automatically follows the commanded path. FELICS uses a 3-Hz to 1/3-Hz video frame rate and JPEG compression of up to 50:1 to drastically reduce the required video data rate.

Further details of the SARGE, TTB, and GECKO systems are provided in [UGV/S JPO, 1995].

ARPA DEMO II PROGRAM

Demo I, a major demonstration of near-term teleoperated UGV capabilities and technologies led by the Army Research Laboratory, was held at Aberdeen Proving Ground MD in the spring of 1992. Beyond Demo I, the focus for OSD's UGV technology development is the ARPA *Demo II* Program. In 1996, Demo II will demonstrate multiple vehicles operating cooperatively under supervised autonomy. Demo II features a familiar cast of participants: Martin Marietta Denver Aerospace is the overall integration contractor, and the co-contractors providing subsystem technologies include Carnegie Mellon University, Hughes Research Laboratory, Advanced Decision Systems, SRI, Teleos, JPL, University of Massachusetts, and University of Michigan. The vehicle platform serving as the *Surrogate Semi-Autonomous Vehicle (SSV)* is the HMMWV, chosen over the STV because of its approximately fourfold advantage in payload weight and volume, doubled ground clearance, and inherent stability. [Gothard, 1992]

Three interim demonstrations have been planned in order to show incremental progress toward the full Demo II capabilities. Demo A, held in July 1993 on the old ALV test track at Martin Marietta's Waterton CO facility, showed basic systems operation and precision navigation on a single vehicle. The principal navigational components were STRIPE (Supervised TeleRobotics using Incremental Polygonal Earth Geometry) and, on well defined road segments, ALVINN (Autonomous Land Vehicle In a Neural Network), both from CMU. Demo B, adding additional capabilities to a single vehicle, was held in the summer of 1994, and Demo C, involving cooperating vehicles, is scheduled for summer 1995. [Chun, 1994]

SECURITY ROBOTS

The site security (sentry) application has a number of features which match the strengths and avoid the weaknesses of UGVs: (1) unlike the RSTA application, the operating environment is known in advance, is under friendly control, and can to some degree be tailored to support robot operations; (2) experience-based costs of inventory shrinkage and non-robotic security measures provide a sound and credible basis for cost/benefit tradeoffs; (3) unmanned vehicles do not get bored during long hours of surveillance, and (4) unmanned vehicles don't participate in "inside jobs".

What is generally regarded as the world's first autonomous security robot, ROBART I, was developed in 1981 at the Naval Postgraduate School [Everett, 1982]. While rich in collision avoidance sensors, this research platform had no sense of its absolute location within its indoor operating environment, and was thus strictly limited to navigating along reflexive patrol routes defined by the relative locations of individual rooms, while periodically returning to a recharging station by homing on an IR beacon.

The second-generation follow-on to ROBART I was ROBART II, which also operated indoors, incorporating a multiprocessor architecture and augmented sensor suite in order to support enhanced navigation and security assessment capabilities. The addition of a world model allowed ROBART II to: (1) determine its location in world coordinates, (2) create a map of detected obstacles and (3) better perform multisensor fusion on the inputs from its suite of security and environmental sensors [Everett, 1990]. ROBART II was transfered to NOSC (now NRaD) in 1986, and used as a testbed for the development of obstacle mapping and other sensor fusion and navigation capabilities.

Two commercial security systems also appeared in the mid-80s. The *Denning Sentry* was an indoor system whose development began in 1983, ultimately involving the investment of several million dollars and contributions from several CMU robotics researchers. Navigation using modulated IR beacons and an enhanced doppler microwave motion detector designed for use on a moving platform were two of the innovations developed by Denning, but ultimately the company went out of business. Meanwhile, Robot Defense Systems (RDS) developed the *PROWLER*, an outdoor sentry/surveillance platform built on a commercial diesel-powered six-wheeled chassis that was capable of following a preprogrammed patrol path with limited obstacle avoidance capability. Video was relayed via microwave back to the human operator, who could override the onboard control computers when necessary. While the PROWLER successfully demonstrated the ability to autonomously follow along a (slightly modified) fence line in a test for the US Army in October 1984, RDS went out of business in 1986. [Everett, 1988]

The Defense Nuclear Agency began a Physical Security Robotics Program in March 1983. Following an initial phase of feasibility studies, DNA has been a major sponsor of Sandia National Laboratories' mobile robotics program. A number of Sandia's robotic systems -- *Dixie*, *RAYBOT*, *Telemanaged Mobile Security Station (TMSS)*, and *RETRIVR* -- are described in [Byrne, 1992].

The *Mobile Detection Assessment and Response System (MDARS)* is a joint Army-Navy development effort to provide an automated intrusion detection and inventory assessment capability for use in DoD warehouses and storage sites. The program is managed by the Physical Security Equipment Management Office at Ft. Belvoir, VA. Overall technical direction for the program is provided by NRaD.

The MDARS goal is to provide multiple mobile platforms that perform random patrols within assigned areas of warehouses and storage sites. The patrolling platforms: (1) detect anomalous conditions such as flooding or fires; (2) detect intruders; and (3) determine the status of inventoried items through the use of specialized RF transponder tags. Separate development efforts target warehouse interiors and outdoor storage areas. The MDARS Interior Program utilizes the Cybermotion *K2A Navmaster* mobility base (equipped with additional collision avoidance, intruder assessment, and product inventory subsystems), and has successfully demonstrated the simultaneous control of two robots patrolling within an interior warehouse environment. The Exterior Program, initiated in February 1993, awarded a contract for the development of the mobility platform to Robotic Systems Technology (RST), and the first prototype exterior vehicle is now undergoing testing. [Gage, 1995]

PLANETARY ROVERS

The use of unmanned robotic spacecraft drastically reduces the cost of space exploration when compared with manned space travel, since robots can be smaller than humans, and eliminating humans also eliminates the need both for complicated and heavy life support systems and for very high reliability in all safety-critical subsystems.

NASA-sponsored development of unmanned vehicles for exploring planetary surfaces began with the JPL Mars Rover in the early 1970s. The program was terminated in 1979, and then restarted in 1986-87 to address a potential 1996 mission, the goal being to provide travel over the Martian surface at up to 10 km per day with partial autonomy, collecting samples as directed from earth. The speed-of-light propagation delay inherent to interplanetary transmission of signals constrains the types of control strategies that can be used in these systems. Complete sessions were devoted to planetary rovers at both the SPIE Mobile Robots III and SPIE Mobile Robots IV conferences [Mobile Robots III, 1988], [Mobile Robots IV, 1989].

JPL has developed two levels of supervisory control relevant to other applications: *Computer Aided Remote Driving (CARD)* and *SemiAutonomous Mobility (SAM)*. In CARD, stereo pictures from the vehicle are displayed in stereo to a human operator, who designates a path for the vehicle to follow as far ahead as he feels he can safely plan. Path parameters are passed to the rover, which executes the path by dead reckoning (with possible vision assistance) and the process repeats. In the Martian scenario, this might mean a typical move of about 20 meters, each move taking about 30 minutes. While this rate might be acceptable for managing scientific sampling in a small area, it would not be suitable for a long distance traverse, which is where SAM would be used. In SAM, a human planner generates a global route through a topographic map of the area generated from images obtained from an orbiter. Both the route and the local topo map are sent to the rover, which executes the move by using autonomous stereo vision to match the topo map. SAM would provide an order of magnitude increase over CARD in average speed of advance. [Wilcox, 1988] Other JPL rover vehicles as of early 1992 include *Rocky III*, *Rocky IV*, *Robby*, and *Go-For* (appears in [Desai, 1992]).

Although lacking the USA's resources to put men on the moon, the Soviet Union has long had an active planetary rover program, with the moon (*Lunokhod*) and Mars (*Marsokhod*) as its two foci. The end of the Cold War has now made Russian research on interplanetary rovers accessible to the point that a Russian Marsokhod vehicle has recently been tested in the California desert under the auspices of the Planetary Society [Burke, 1995]. Descriptions of Russian systems and pointers to the Russian literature are found in [Kemurdjian, 1995].

INTELLIGENT VEHICLE / HIGHWAY SYSTEMS (IVHS)

A final thread of UGV development is the area that has become known in the US as *Intelligent Vehicle/HighwaySystems*, or *IVHS*. Fueled by gasoline tax dollars, IVHS is a major DOT initiative; the goal of the *Automated Highway System (AHS)* component of IVHS is "to significantly improve the safety and efficiency of the nation's surface transportation system through a national effort that best ensures the early, successful deployment of automated vehicle control technologies in both partial and eventual fully automated systems" [Bishop, 1994]. IVHS/AHS clearly involves huge economic and legal issues as well as major technological ones. In the context of our discussion here, public highways represent a specific system operating environment possessing significant structure (and the possibility of deliberately adding more structure to support automated operation), enormously complicated by the presence of numerous other vehicles operated by human drivers. Dickmann's group in Münich has been a leader in autonomous driving on "live" highways: "The autonomous vehicle VaMoRs-P has shown its performance capabilities and robustness on a much used freeway near Paris, the Autoroute A1, in September 94 by chauffeuring international experts through heavy traffic at speeds up to 130 km/h (the French speed limit) under various lighting conditions and even during light rain fall." [Maurer, 1994]

SUMMARY "STORY LINE"

The development of autonomous mobile robots with non-trivial navigational capabilities began as an interesting "application domain" for Artificial Intelligence researchers in the late 1960s, and continues to present major challenges to researchers and system developers today. Developers have envisioned unmanned vehicles, whether autonomous, teleoperated, or under supervisory control, as the solution to real-world requirements in application areas such as RSTA, physical security, and planetary exploration. The Army and the Marine Corps each pursued a number of battlefield (RSTA and weapons-launching) UGV developments in the 1980s, and demonstrated the feasibility and potential value of such systems. Since about 1990, DoD unmanned vehicle development efforts have been fully consolidated under OSD, with the UGV/S JPO pursuing the formal acquisition process for the TUGV, and ARPA working in parallel to develop necessary enabling technologies. A major and continuing element of the JPO's activities has been the accelerated development of a number of prototype systems for evaluation by prospective user communities.

FOR ADDITIONAL INFORMATION

As a brief scan through the references listed below demonstrates, information on unmanned ground vehicles / mobile robots is readily available from a number of sources. Formal presentations of technical details typically appear in the Proceedings of the IEEE International Conference on Robotics and Automation, the Proceedings of the SPIE Mobile Robots Conference, and other SPIE conferences focused on optical and other sensors, all held annually. Less technical, more programmatically-oriented presentations, especially of defense-related systems, are found in this magazine (Unmanned Systems), and in the Proceedings of the AUVS Annual Symposium. Descriptions of systems for the space and nuclear powerplant environments usually appear in journals and conference proceedings focused on these industries (e.g., American Nuclear Society Topical Meetings on Robotics and Remote Systems).

In addition to written materials, an increasing amount of information on robotics is becoming available on the Internet, the most user-friendly access method being the World Wide Web. For an introduction to the Web, see [Gage, 1994], or consult your local computer guru. Useful Web starting points include the *Robotics Internet Resources Page* [URL-Robotics] at the University of Massachusetts and the *Computer Vision Home Page* [URL Vision] at Carnegie Mellon. These focus principally on university research groups and projects that serve information on the Internet, while the *comp.robotics Frequently Asked Questions (FAQ)* [URL - FAQ] provides pointers to more diverse robotics resources such as robot clubs and societies around the world, magazines of interest, and component manufacturers. Non-academic UV efforts are not yet well-represented on the Internet. The ARPA UGV Demo II Project is in evidence through the CMU's *NavLab* Web pages [URL- NavLab] and University of Michigan's UGV pages [URL - UMich/UGV], and Martin-Marietta makes Demo II project data available to approved users (associated project participants) through an anonymous ftp server. Also, try out the "under construction" *AUVSI Homepage* [URL- AUVS], and look for a new DTIC-sponsored UV database coming from AUVS later this year [Thurman, 1995].

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