Autonomous Vehicles for Space Exploration and Terrestrial Applications

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ABSTRACT

Current research and development work on autonomous space exploration using planetary rovers is briefly outlined with the purpose of analyzing the rationales and goals that lead to the design of the autonomous vehicles and identifying the main differences w.r.t. the design of autonomous vehicles for terrestrial applications. A brilliant opportunity to transfer and further enhance some of the most advanced methods and techniques of autonomous space exploration using planetary rovers to terrestrial applications is provided by the current realization of a series of races for autonomous robotic ground vehicles, which has challenged the corresponding communities of researchers and technologists. A third version of the race has taken place in an urban environment while the two first versions of the race held in open terrain had clearly shown how difficult the task really is. A substantial improvement of the whole field has been enabled by the competitions, while real-time capabilities are still missing in space robotic explorers.

Keywords: Autonomous Vehicles, Control, Flying Robots, Intelligent Systems, Mechatronics, Multisensory Fusion, Navigation, Perception, Planning, Space Exploration, Space Robotics, Vision.

INTRODUCTION

Since the early eighties we have been working on almost all areas and technologies of manned and unmanned spaceflight including among others, planning of interplanetary missions (1) and the development at the turn of the millennium of the most advanced spacecraft ever built at NASA JPL in Pasadena, California to fly to the Jupiter moons and Pluto, i.e., to the frontiers of our solar system. With my consortium as national prize winner in the United States of America, we used for interplanetary missions gravitational assist techniques to practically develop economic, fuel-saving navigation strategies for spacecraft, e.g., in the design for NASA of micro-spacecraft and a series of micro-missions to Mars, which is also available for the first private mission to an asteroid.

Our work on autonomous space exploration systems, and more particularly, on intelligent, autonomous robots, has been very intensive, i.e., space-related and autonomy/intelligence research and development could be carried out with similar intensity. The combination of these two areas of activity led to the research and development of concepts, system design and development, missions, and strategies for advanced space exploration and colonization using autonomous robotic systems with or without human cooperation/interaction (2). All perspectives of the study of intelligence were covered: artificial, behavioral, computational, and more recently biologically-inspired intelligence.

From the very beginning, we were lucky enough to have been pioneering and leading these areas world-wide. Examples include my participation at the First International Conference on Telerobotics held at NASA JPL in Pasadena, California in 1988, where a potential, technologically deeper DLR-NASA cooperation was explored to incorporate feedback in teleoperation and autonomous space robotics. We finally demonstrated successfully telerobotics and autonomous robots during the DLR D2 space mission with NASA's Spaceshuttle Columbia (STS-55 flight), ESA's Spacelab, and DLR's space robot ROTEX in 1993. The spectacular results of those experiments utilizing a symbiotic cooperation between teleoperators, astronauts, and intelligent autonomous robots were reported upon special invitation world-wide including at the main NASA and ESA centers. All those activities have built the foundations for more current efforts leading to the development of robonauts, the robotic-artificial version of (human) astronauts.

The subsequent references are meant to be provided as representative work of a vast amount of literature in the subject and are by no means exhaustive. General principles of intelligent robots/vehicles (3) (4) (5) and successful case studies (6) have been described in the literature. Other treatments cover specific aspects like vision in general (7) or more space-mission-specific (8) (9), sensors (10), multisensory fusion (11), terrain modeling and map building (12) (13), behavior-based and learning control (14) (15), navigation (16), computational aspects (17) (18), and architectures (19) (20). Performance tests with space mission rover prototypes have been conducted and their results have been reported (21) (22) (23). Contributions to advanced concepts and improvements have been provided (24) (25) including fundamental principles for flying robots for autonomous space exploration (26) (27).

AUTONOMOUS SPACE EXPLORATION

Current approaches for autonomous space exploration, more specifically, for Mars exploration using planetary rovers, take into account considerations that factually result in severe constraints for their utilization in terrestrial applications and call for the expeditious enhancement of research and technology development in the area of autonomous robots and vehicles per se. This appears to be a contradiction, but let us briefly examine some of the arguments involved. Figure 1 shows on the left side my team's prototype miniature rover design for ESA's first mission to Mars in the early 1990's and for collaborative work with NASA in the early 2000's on the right side. Let us start by the direct and practical observation that the speed of Mars rovers, e.g., the NASA MERs, is currently fairly low. On the one hand, a speed improvement in the context of space exploration would be obviously desirable. The same could be stated w.r.t. the need for higher autonomy.

On the other hand, the design of planetary rovers, more specifically, their mission operability, is guided in general by the requirement to operate very robustly, to show autonomy, and the ability to handle resource constraints and unpredictable events. Overall design solutions include contingency planning on the ground and flexible, robust execution of conditional sequences on board. The final goal of the on-board executive is defined as maximizing the science return. Here is where one of the key issues is. High speed of command execution might be desirable, but if the mission goals are accomplished robustly with less autonomy on-board and taking longer, that is not highly detrimental to the mission's goals or science return. On the other end, the breadth and depth of the most advanced research and development for implementing local autonomy in planetary rovers represents a wealth of contributions for their terrestrial application counterparts. However, further improvements are required as we will show.

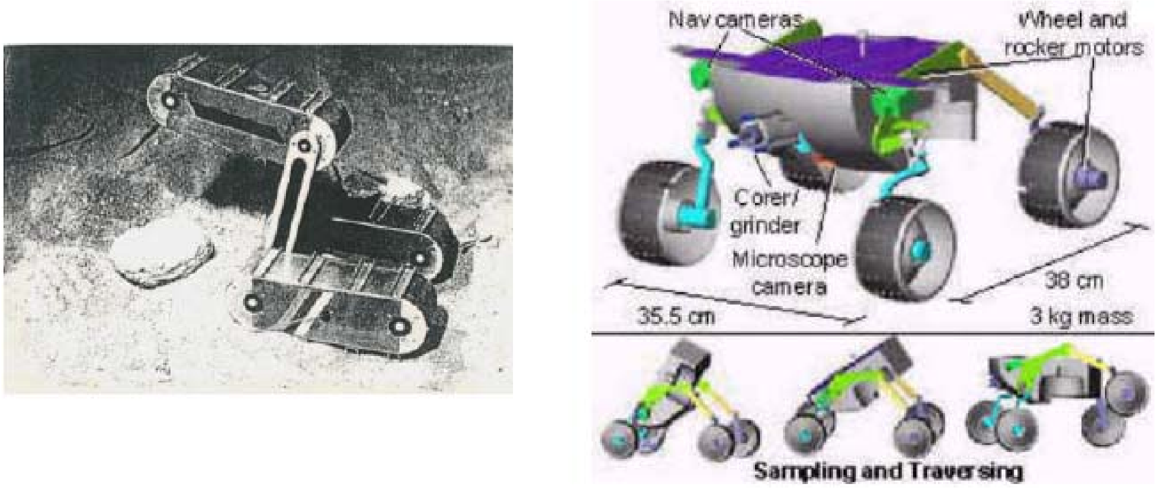

Figure 1 Miniaturized Rovers designed with/for ESA and NASA

THE GRAND CHALLENGES

Beginning in 2004 the U.S. American Defense Advanced Research Projects Agency (DARPA) has been organizing a series of races for autonomous robotic ground vehicles. The agency manages and directs basic and applied research projects for the U.S. Department of Defense (DoD). The race route is made of off- and on-road terrain cleared of interfering vehicles not participating in the race. Only unmanned autonomous ground vehicles are allowed to participate that are capable of completing the entire route without external communications or human (remote) control.

The overall requirements of the initial race were conceived as follows. The route is defined by a series of waypoints with maximum time limits for vehicles to negotiate them. Vehicles crossing the boundaries defining the route are penalized. Autonomous service, repair, and refuel is provided by additional checkpoints. Prior to the main event, there is a qualification, inspection, and demonstration (QID) event. To be selected, the teams are also required to submit a technical paper that is rigorously evaluated. The team that most quickly completes the course in less than 10 hours wins the race.

The first race took place in March 2004 in the desert between Barstow, California and Primm, Nevada, U.S.A., cf. Figure 2. The QID event took place at the California Speedway in Fontana, California. From 106 teams initially submitting applications to participate, 86 teams submitted technical papers, and the final field of participants had only 25 teams. Of these 25 teams, only 15 teams passed the one-week long QID event to actually participate in the main event. No team could win the main event, even worse, no team could arrive in Primm, Nevada. Of the approximately 142 miles of the course, the best team, the Red Team, reached 7.4 miles and was then command-disabled because it had gone off-course, got caught on a berm, and the front tires had caught fire.

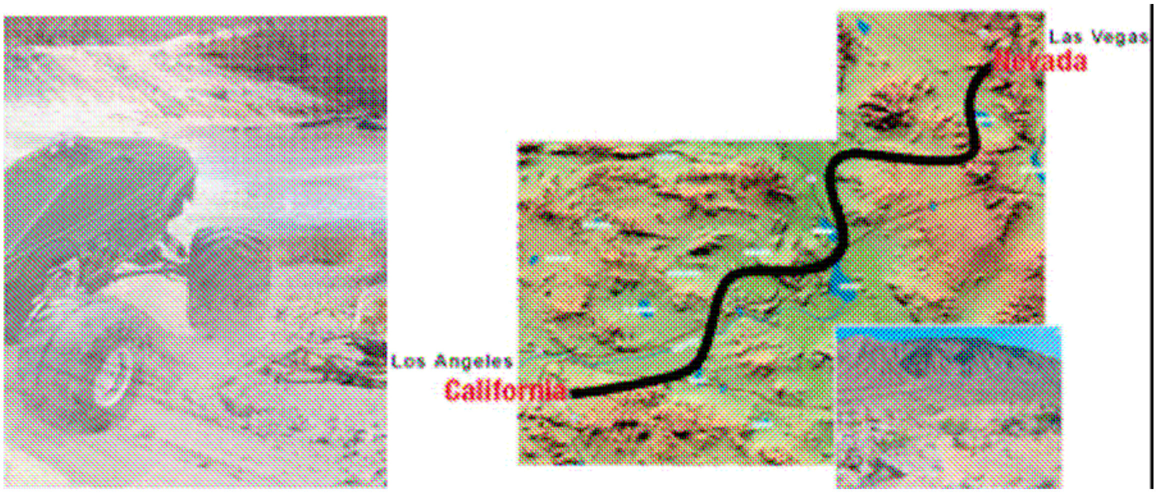

Figure 2 DARPA's Grand Challenges – 2004 Route

The second race in the series took place in October 2005. Figure 3 shows main aspects of the course. Five vehicles finished the 132-mile route. The final results and the first three teams (1. Stanford Racing, 2. Red Team, 3. Read Team Too) are shown in Figure 4 and Figure 5 respectively. Their average speed was 19.1, 18.6, and 18.2 mph respectively.

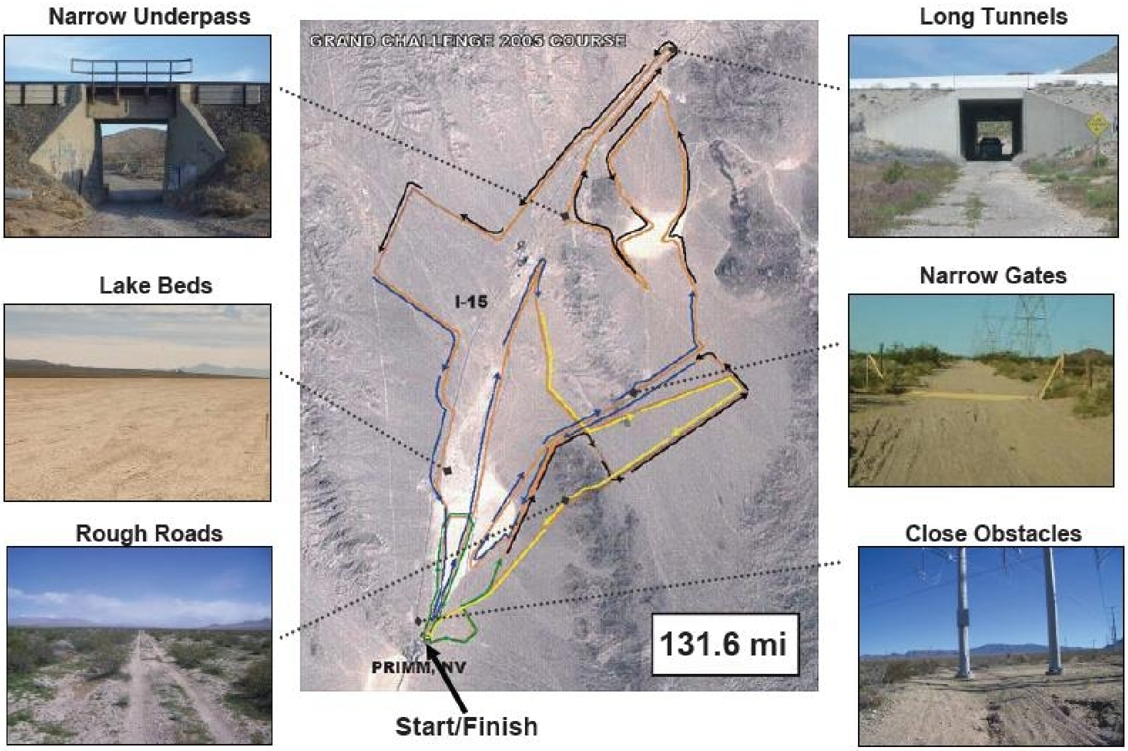

Figure 3 2005 Grand Challenge – The Course

ID	TEAM	TIME	DISTANCE
3	Stanford Racing Team	6h 53m	131.70
19	Red Team	7h 4m	131.70
25	Red Team Too	7h 14m	131.70
30	Gray Team	7h 30m	131.70
21	Team TerraMax	12h 51m	131.70
28	Team ENSCO	DNF	81.20
23	Axion Racing	DNF	66.20
38	Virginia Tech Grand Challenge	DNF	43.50
9	Virginia Tech Team Rocky	DNF	39.40
10	Desert Buckeyes	DNF	29.00
4	Team DAD (Digital Auto Drive	DNF	26.20
14	Insight Racing	DNF	25.60
1	Mojavaton	DNF	23.00
18	The Golem Group / UCLA	DNF	22.40
24	Team CajunBot	DNF	17.20
20	SciAutonics/Auburn Engineer	DNF	15.90
15	Intelligent Vehicle Safety Tecl	DNF	14.00
8	CIMAR	DNF	13.60
41	Princeton University	DNF	9.50
26	Team Cornell	DNF	8.90
2	Team Caltech	DNF	8.00
16	MonsterMoto	DNF	7.20
37	The MITRE Meteorites	DNF	0.73

Figure 4 2005 Grand Challenge – The Final Results

Figure 5 2005 Grand Challenge – First Three Teams

The third version of the competition called the Urban Grand Challenge was held in an urban environment in Victorville, CA in November 2007. The event featured autonomous ground vehicles maneuvering in a mock city environment, cf. Figure 6, executing simulated military supply missions.

Figure 6 DARPA Grand Challenge – Supply Mission

During the Urban Grand Challenge, robotic vehicles attempted to complete a 60-mile course through traffic in less than six hours, operating under their own computer-based control. The actual course length was about 55 miles. Live traffic was simulated by approximately 50 human-driven traffic vehicles. To succeed, vehicles had to obey traffic laws while merging into moving traffic, navigating traffic circles, negotiating busy intersections and avoiding obstacles. The entire task for each of the competing autonomous vehicles was subdivided into three missions, each consisting of 6 or 7 subtasks. After each completed mission, the vehicles had to return to the start area to have a new mission file loaded and its sensors cleaned off by the team's pit crew. Figure 7 shows the course in Victorville, CA to the left. In the middle, the collision between the teams from MIT and Cornell is shown. To the right, the DoD / U.S. Army's Stryker is shown, an armoured personnel carrier (APL) used in Iraq, which is an eight-wheel combat vehicle, only semi-autonomous, i.e., it still requires partially a driver to be operated.

Figure 7 2007 Urban Grand Challenge in Victorville, CA

Six of eleven vehicles that started in the final event finished the entire course, only four accomplished the tasks in under the allotted 6 hours. The 11 teams had been selected from a field of 35 semifinalists after participating in the National Qualification Event (NQE). Figure 8 shows the three competition winners: CMU's Boss (left, 1st place), Stanford's Junior (mid, 2nd place), and Virginia Tech's Odin (right, 3rd place). MIT's Talos finished fourth (no prize). The average speed of the first two was 14 and 13 mph respectively. The DoD aims to make one third (1/3) of its supply fleet robotic (fully autonomous) by 2015.

Figure 8 2007 Urban Grand Challenge – First Three Teams

BRINGING SPACE RESEARCH AND TECHNOLOGY DOWN TO EARTH

There is a significant amount of interest world-wide in the research and technology communities about the issues raised by the races previously described. Participating teams pursue to win the race obviously and the industry is seeking substantial business from associated contracts from the military. The commercial industry is also heavily participating, its interest being to incorporate this type of technologies into the car of the future, e.g., with driving assistance and collision avoidance mechanisms. In general, the approach to appropriately mix local autonomy capability based on a real-time multisensory processing approach with semi-global guidance by GPS navigation satellites has proven to be sound given the rules provided by the organizers. In both areas, the author has provided over the years world-wide leadership. Figure 9 shows the first real-time local perception engine for providing local autonomy that we designed and developed for space autonomous robots in the late 1980's and early 1990's and was demonstrated successfully with NASA, ESA, and DLR in a Spaceshuttle mission, the STS-55 flight of the Columbia. Figure 10 shows my design for highly advanced aircraft avionics including global navigation capabilities based on integrated GPS/INS for the U.S. government (DoD) in the late 1990's. Figure 11 shows some of my work on advanced concepts for autonomous flying and ground vehicles for space exploration in the 2000's.

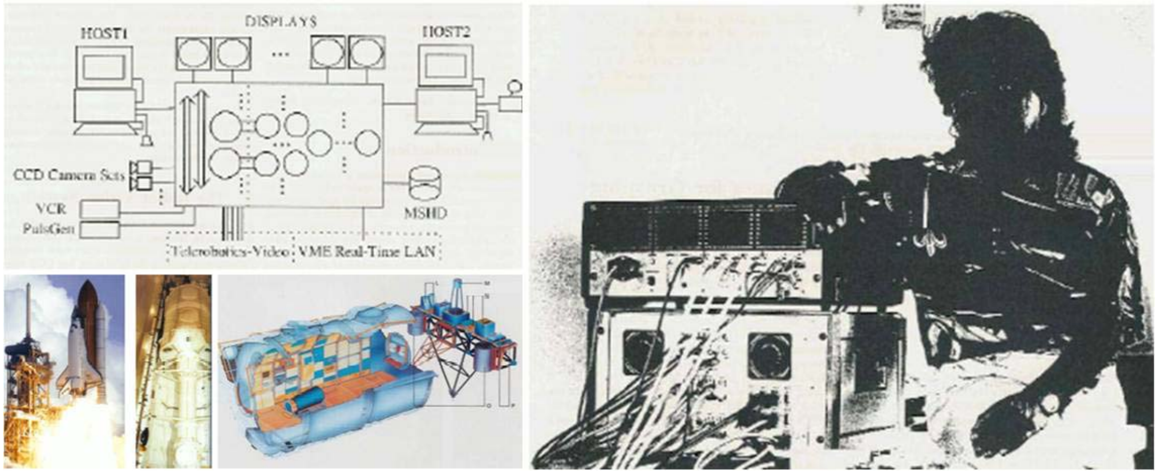

Figure 9 Local Perception in Real-Time for Autonomous Robots

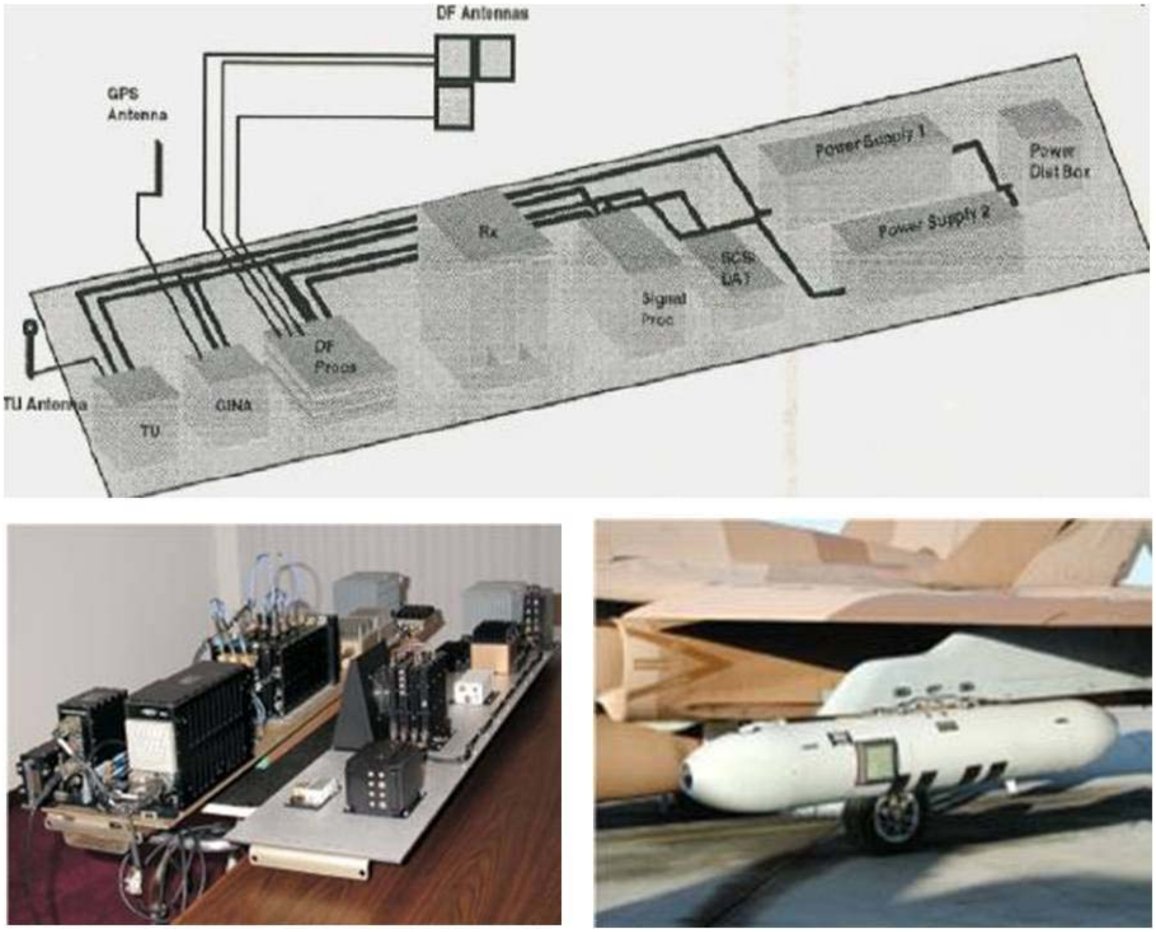

Figure 10 Advanced Aircraft Avionics with Satellite-Based Global GPS-INS Guidance

Figure 11 Advanced Concepts for Autonomous Flying and Ground Vehicles for Space Exploration

While some of my approaches and systems are beyond solving the Grand Challenge features, let us take a look at the cutting-edge w.r.t. solutions fulfilling the requirements in the framework of the past competitions. The winner team vehicle of the 2005 Grand Challenge (28) was based on a Diesel Volkswagen Touareg R5 with variable-height suspension, outfitted with custom skid plates and a front bumper to protect the vehicle from environmental impact. The vehicle called Stanley was throttle-, brake-, and steer-by-wire. Vehicle data was transferred to the computing system via a custom CAN bus interface. Algorithmic foundations can be found in (29).

Most sensors are held on top of the custom roof stack including five (5) SICK laser range finders pointed into the driving direction, a color camera also pointed forward and angled slightly downwards, and two antennae of the forward-pointed RADAR system, all these sensors for environment perception, as well as one antenna for GPS, two additional GPS antennae for the GPS compass, the DARPA emergency E-stop communications antenna, a horn, and a signal light. Three (3) additional E-stop GPS antennae are directly attached to the roof.

The computing system, see Figure 12 left, was placed in the trunk featuring a shock-mounted rack carrying an array of six (6) Pentium M Blade computers, a Giga Ethernet switch, and various devices interfacing to the physical sensors and actuators. A 6-DOF Inertial Measurement Unit (IMU) was rigidly attached to the vehicle frame underneath the computing rack in the trunk. Figure 12 right shows the drive-by-wire system and the interface for manual vehicle operation.

Figure 12 Computing System (left) and Drive-by-Wire System (right)

Raw sensor data for environmental perception come from the laser, vision, and radar systems of the vehicle. Figure 13 (left) shows typical laser data. The sensor data is integrated into a single model of the environment called the drivability map. Grid cells of the drivability map are shown white, red, or grey corresponding to drivable terrain, obstacle, or unknown terrain respectively, see Figure 13 (right).

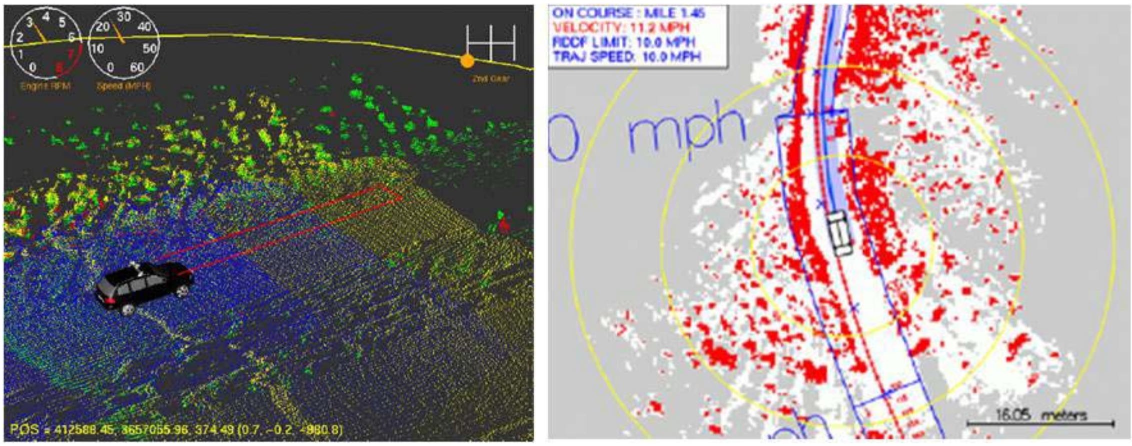

Figure 13 Laser Range Data and Drivability Map

Innovative subsystems have been developed, e.g., rotating 64-sensor LIDAR systems, see Figure 14, capable of full azimuthal coverage operating at rates needed for moving vehicles. The one on top is an intermediate prototype. The one at the bottom is the state of the art prototype, which is outlined in the sequel. Fields of view are 360° HFOV (horizontal) and 26.8° VFOV (vertical). Its frame rate is user-selectable (5-15 Hz). At 15 Hz, the unit spins at 900 RPM to gather data. The interface to the end user is a 100 Mbps Ethernet, its output rate is over 1 Mio. points per second. In contrast to traditional LIDAR sensors that rely upon a single laser firing into a mechanically actuated mirror providing only a single plane of view, this innovative one-piece design uses 64 fixed-mounted lasers, each mechanically mounted to a specific vertical angle, with the entire unit spinning. This type of design substantially increases reliability, FOV, and point cloud density.

Figure 14 Rotating 64-Sensor LIDAR Systems

The example point cloud image in Figure 15 shows the vehicle at an intersection with other vehicles in its vicinity along with road features. The HDL-64E provides high definition 3-dimensional information about the surrounding environment. Applications include military and commercial autonomous vehicle navigation, automotive safety systems ground truth testing, 3-D mapping, surveying, and robotics (30), technical details can be found in (31).

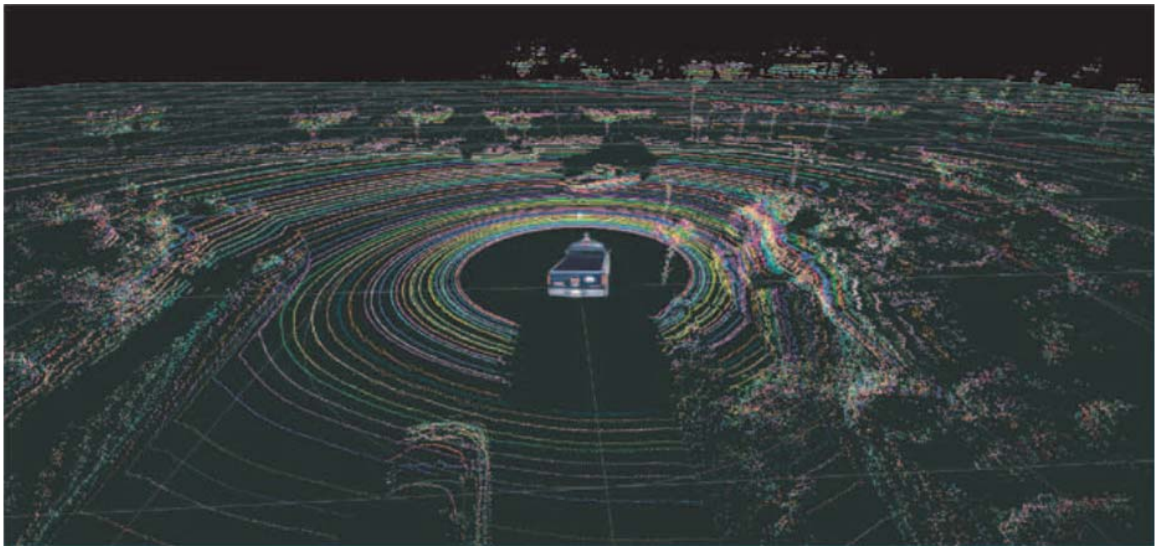

Figure 15 Point Cloud Image of a High Definition LIDAR HDL-64E

Some of the early pioneering work on autonomous vehicles goes back to the VaMoRs (Vehicle for autonomous Mobility and Computer Vision) and VAMP (VaMoRs-Passenger Car) vehicles, whose achievables are currently being continued with the MuCAR-3 (Munich Cognitive Autonomous Robot Car, 3rd Generation) vehicle. Figure 16 shows the VaMoRs vehicle (1985-2004) equipped with computer control of throttle, break, and steering. Its initial video image processing was executed on five (5) Intel 8086 16-bit processors.

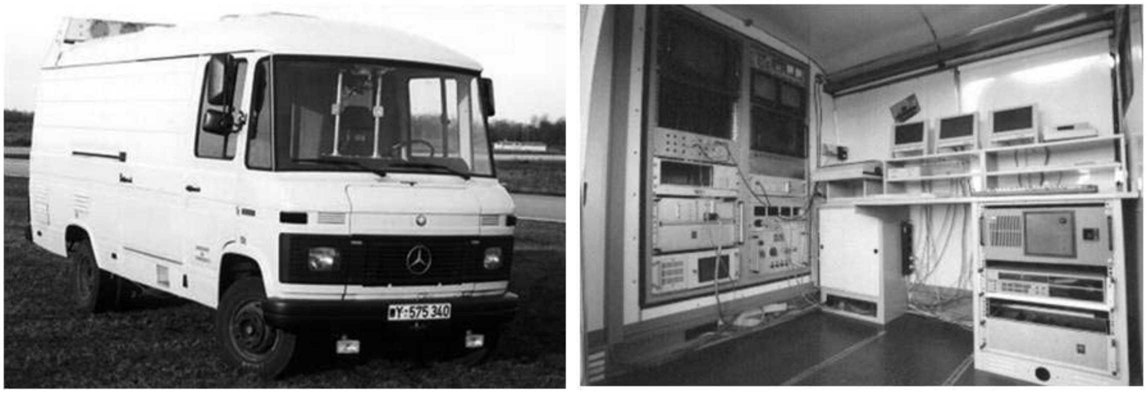

Figure 16 Vehicle for autonomous Mobility and Computer Vision (VaMoRs)

VAMP had two pairs of bifocal camera sets with focal lengths 7.5 and 24 mm, one looking to the front and the other looking to the rear of the vehicle. An array of 320 by 240 pixels per image was used, this allowed to observe the road and traffic up to 100 m in front and behind the vehicle. The image processing engine composed of 46 parallel processors was able to recognize road curvature, lane width, number of lanes, type of lane markings, its own position and attitude relative to the lane and the driveway, and the relative state of up to ten other vehicles including their velocities, five in each hemisphere.

At the final demonstration of the EUREKA project near Paris, France, VAMP showed free lane driving and convoy driving at speeds up to 130 km/h in dense three-lane traffic, lane changing for passing, and autonomously deciding whether lane changes are safely possible. The final go-ahead by provided by a human safety pilot after checking the decision validity. By increasing the processing power by an order of magnitude, a test over 1600 km in Denmark in 1995 showed that 95% of the distance could be traveled fully autonomously, in both longitudinal and lateral degrees of freedom, the maximum speed reached was 180 km/h.

The MuCAR-3 is shown in Figure 17 (left). It is based on a VW Touareg V6 TDI, fully drive-by-wire capable. The computing power consists of a quad-core Opteron PC and two dSPACE systems for low level control of the camera platform and the vehicle control. The actuators include throttle, brake, steering, parking brake, and position select for automatic gearbox. The sensors include vehicle status data, odometer, inertial navigation system, active multifocal camera platform MarVEye 7, and a high definition 360º Lidar. As an example of the complex processing performed, the road tracker for country roads and dirt tracks is based on the 4-D approach, Figure 17 (right). This as well as related principles and algorithmic foundations of dynamic vision for perception and control of motion can be found in (32).

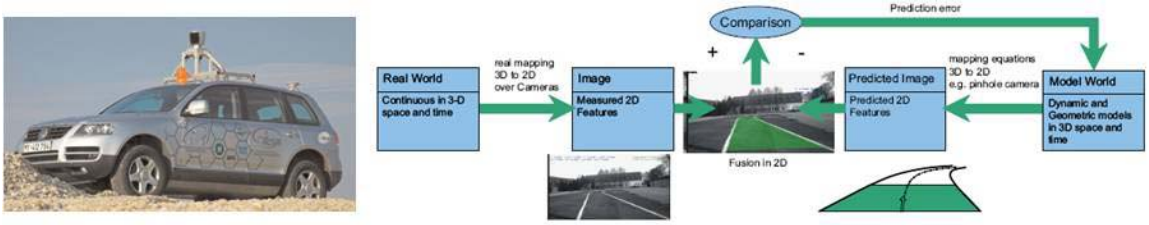

Figure 17 MuCAR-3 and 4D Approach for Road Tracking

For the 2007 Urban Grand Challenge, the autonomous vehicles - equipped with a number of lasers, cameras, and radars to sense the environment - had to be able to:

- follow rules of the road,
- detect and track other vehicles at long ranges,
- find a spot and park in a parking lot,
- obey intersection precedence rules,
- follow vehicles at a safe distance, and
- react to dynamic conditions like blocked roads or broken-down vehicles.

Most of the above features are obviously not required for space exploration vehicles, at least not in the near future. The terrestrial robotic vehicles needed to navigate autonomously in town and traffic. For that purpose, perception, planning, and behavioral software were used to reason about the traffic and the proper actions to take to safely arrive at the final destination. The main characteristics of the winner team vehicle of the 2007 Urban Grand Challenge, Boss (33), are summarized below:

- the vehicle base is a 2007 Chevy Tahoe,

- the driveline includes a 5.3LV8, 4L60 automatic transmission, 4wd, E-85 fuel-capable,
- drive-by-wire: GM engine control, electromechanical actuation,
- maximum autonomous speed: 30 mph,
- Radar: five (5) Continental ARS300 (long range),
- Lidar: eight (8) SICK LMS-291 (short range), Velodyne HDL-64 (mid range), two (2) steered Continental ISF 172, two (2) IBEO ALASCA XT (long range),
- Pose estimation: Applanix mPOS-LV with dual antenna GPS and IMU,
- Computing: ten (10) Intel Core2Duo blades @ 2.16 GHz in a compact PCI chassis,
- Software architecture: decentralized, multi-processor system coordinated via Gigabit Ethernet communications layer,
- Planning: motion planning evaluates over 1000 candidate trajectories per second,
- Perception: multi-sensor fusion generates moving and static obstacle models,
- Behavioral: context-centric reasoning makes tactical decisions.

Now, going back to the space environment, Figure 18 (left) shows the testing navigation tasks of the MER in the new NASA JPL testing facility that we shared with the MER team while my team and I were building the most advanced NASA spacecraft to be sent to the Jupiter moons and Pluto. Figure 18 (right) shows stereo vision for MER autonomous navigation, reminiscent to the algorithms and systems I designed and deployed in the early 1990's, but systems that already at that time ran at much higher throughput, i.e., in real-time. Figure 19 outlines the daily traversability of NASA's Spirit MER on the Red Planet.

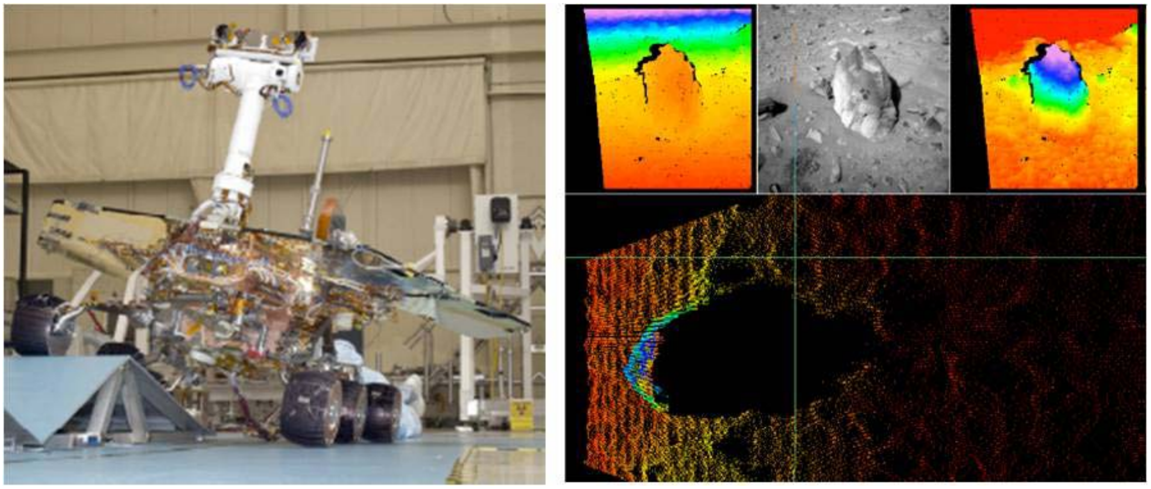

Figure 18 Testing MER Navigation (left) and Stereo Vision for MER Autonomous Navigation (right)

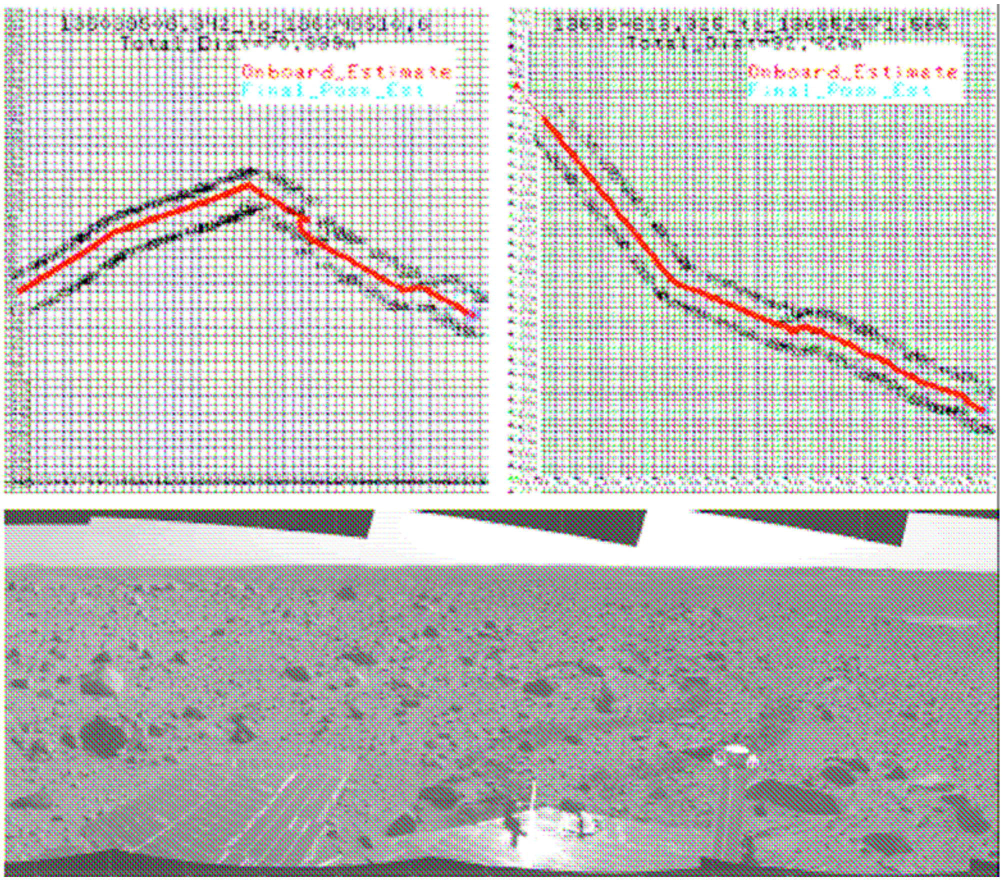

Figure 19 Spirit MER Daily Traversability on the Red Planet

It is thus fair to say in accordance to my previous statements that computing technology being sent to space lacks the performance to execute vital navigation tasks in a faster manner, also in relation to its applicability to terrestrial applications like those reminiscent to the Grand Challenge scenarios. In the case of the MERs, the baseline autonomous navigation system includes only local obstacle avoidance with stereo vision. There is no onboard global mapping, global path planning, or global localization functions. The MER flight processor is the RAD6000, a radiation-hardened version of the PowerPC CPU running vxWorks as Real-Time Operating System (RTOS), which allows, e.g., the computation of the onboard stereo vision algorithm delivering XYZ range images in 24 to 30 seconds per image pair. A brief answer to that state of affairs is to rebuild our real-time perception systems of the late 1980's and early 1990's with miniaturized space-qualified architectures of the late 2000's for NASA, DoD, and others as we have repeatedly done recently for the private terrestrial industry.

CONCLUSIONS

New opportunities to advance the state of the art in space exploration through enhanced autonomy of planetary rovers and the transfer of some of the most advanced methods and techniques to terrestrial applications were outlined. The different drivers in the design of autonomous vehicles for space exploration and for some terrestrial applications were emphasized. The appropriate combination of local autonomy based on real-time multisensory perception and semi-global guidance based on navigation (GPS, GLONASS, in the future GALILEO) satellites has shown to offer a solution path to the difficult task of autonomous navigation through open terrain and with additional logic also in town and traffic for terrestrial applications, both military and commercial. There is much need to enhance the algorithmics and throughput sent to space to provide our exploratory and soon also our colonization vehicles with superior real-time capabilities.

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