2012 ROBOTICS ACTIVITIES AT JPL

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Richard Volpe [(1)]

[(1)] Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Drive, Pasadena, California, 91109
Email: volpe@jpl.nasa.gov

ABSTRACT

The Robotics Section of the Jet Propulsion Laboratory (JPL), California Institute of Technology, is engaged in a full spectrum of flight project and research activities. This paper will provide an overview of these efforts, and discuss the recent accomplishments and future directions of them. Specific activities will be highlighted based on their level of accomplishment, impact on the community, maturity, or novelty. Robotics activities on flight projects are a significant subset of the full effort for these large missions. Complementing flight activities is a diverse set of research efforts for NASA and other U.S. Government agencies. Future directions will be motivated by NASA and other sponsor objectives, as well as success experienced in these current endeavours.

1. FLIGHT PROJECTS

Currently, JPL Robotics is continuing to participate in the operation of the Mars Exploration Rover (MER), Opportunity, even while preparations are being finalized for the operation of the Mars Science Laboratory Rover (MSL), Curiosity, to begin in August 2012. Many of the roboticists are area experts who are invaluable to mission operations because they have also developed the hardware and software systems on-board the robotic spacecraft, including drilling, manipulation, and surface navigation subsystems. Additionally, beyond the Mars rover projects, JPL Robotics is actively engaged in proposal development and robotic subsystem prototyping for future mission concepts targeted for Mars, the Moon, and Primitive Bodies in the solar system.

1.1. Mars Science Laboratory (MSL)

MSL is currently on the way to Mars and will have landed on 5 August 2012, a month before the presentation of this paper at the i-SAIRAS conference. Within that month, it is possible that the spacecraft will have completed its system check-outs and begun its surface operations at Gale crater. JPL Robotics personnel have directly created, led in the implementation, or played important roles in the flight development of several key capabilities for the MSL system. These include surface system algorithms and software for rover vision and navigation, manipulator development, drilling, and motor control. Additionally, they have developed algorithms and software for: operations interfaces; rover and spacecraft simulation for mission planning and reconstruction of entry, descent, and landing (EDL); and terrain analysis of Gale crater orbital imagery for mission planning. Several major activities have been led directly by robotics personnel (as lead engineer, contract monitor, or task manager) including the development of: the manipulator, drill, and surface system software; engineering interface for rover driving; and the vehicle integration for Assembly, Test, and Launch Operations (ATLO).

From an engineering perspective, the MSL system is an evolutionary improvement over its predecessors, the Mars Exploration Rovers (MER), and the Sojourner Rover, engineering models of which are seen in Fig. 1. Although MSL is roughly four times the mass of MER, several key features of its layout remain the same, including: six wheeled rocker-bogey suspension; stereo vision camera pairs on the front, back, and mast; and a five degees-of-freedom (DOF) robotic arm with integrated instrument turret. This system layout, and the operations tempo for it, was first prototyped in the mid 1990’s as part of a focused technology development

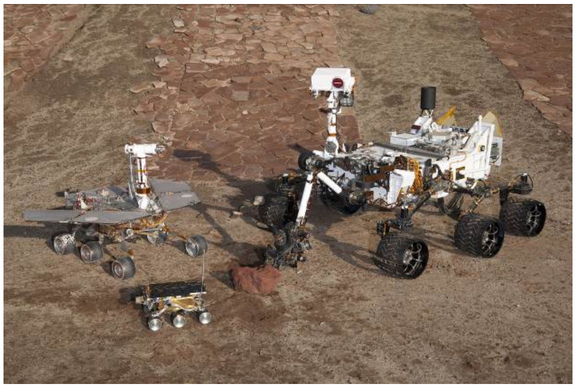

Figure 1: A family portrait of Mars rover engineering models, with MSL (right), MER (left), and Sojourner (center).

program at JPL [1]. Similarly, MSL software subsystems such as Grid-based Estimation of Surface Traversability Applied to Local Terrain (GESTALT) navigation shown in Fig. 2, and the Rover Sequencing and Visualization Program (RSVP) showing in Fig. 3, have development threads that trace back to research efforts decades prior [2,3]. It is important to appreciate this technology development and infusion track record, as new technology development efforts are described later in this paper.

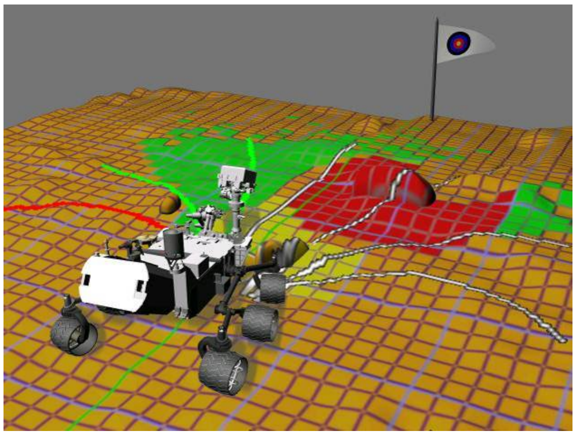

Figure 2: A graphical representation of the GESTALT navigation algorithm, where safe terrain for driving is shaded green, and unsafe red.

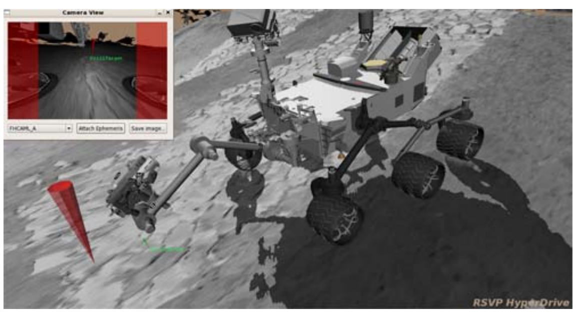

Figure 3: One view from the RSVP HyperDrive operator interface, showing the MSL model on a terrain model created from rover imagery.

1.2. Mars Exploration Rovers (MER)

One of the two MER vehicles, Opportunity, is still active on the surface of Mars. To date, the rover has traversed approximately 34.5 km over the past 8.5 Earth years. The most recent terrain being explored is in the Endeavour crater, with Opportunity currently near one edge of the 22 km diameter depression. Given the size and different geology within the basin, it is anticipated that the rover will be exploring it for years to come.

Robotics personnel continue to be intimately involved in the operations of MER. Expertise has been acquired through years of rover driving and manipulation sequence development, and this expertise has been used to refine the processes and operational envelope for efficiency and safety. Some of our MER personnel have migrated to MSL and are preparing for operation of that system. Others have brought their experience back into the research sector and participate in new system development and operation. Tools such as RSVP have not only migrated to MSL, but have been employed on other Projects such as the Mars Phoenix Lander [4], and future mission concept testbeds, discussed below.

1.3. Mission Proposals

While large flight projects like MSL and MER have been assigned to JPL by NASA, there are open competitions held for smaller missions in the NASA New Frontiers and Discovery Programs. Several of these mission concepts have been for in-situ missions, and therefore attract and benefit from the involvement of JPL Robotics.

1.3.1 Venus Balloon

Venus balloon technology development has concentrated on material investigation, balloon design, inflation tests and aerial deployment of prototype systems [5]. Issues addressed in the research have been robustness to sulphuric acid which is present in the target altitudes of the Venusian atmosphere, material stress from folds in the packaged system, and loads experienced during deployment. Each step of the research has been designed to retire risk and confirm the viability of the technology for mission use, and the resultant technology has been included in a Discovery Program proposal for the "VALOR" mission to Venus.

1.3.2 Venus Surface Sampling

In the last New Frontiers proposal cycle, JPL had two mission concepts reach step 2, which culminated in a site visit by the selection review board. One of these two proposals was for a Venus lander called the Surface and Atmospheric Geochemical Explorer (SAGE) [6]. This mission proposed to use a Raman and laser-induced spectrometer (LIBS) to measure the terrain and subsurface exposed by a robotic arm. JPL Robotics personnel led the development of the testbed and arm used for demonstration of this concept during the site visit.

1.3.3 Lunar Sample Return

Another participant in the same New Frontiers competition was the Moonrise mission proposal to land in the lunar South Pole Aitken Basin, sample the regolith, and return samples to Earth. Since the proposed landing site did not have line of sight communication to earth, and to provide contingency capability if relay communication through an orbiter was not operational, this system required scalable autonomy to perform its sampling operation. The proposed nominal operation borrowed heavily from Mars Phoenix mission structure and tools, with uplink and downlink cycles framing autonomous digging operations. A full-scale testbed, shown in Fig. 4, was built to demonstrate successful regolith sifting, containerization, mass determination, and return capsule transfer [7].

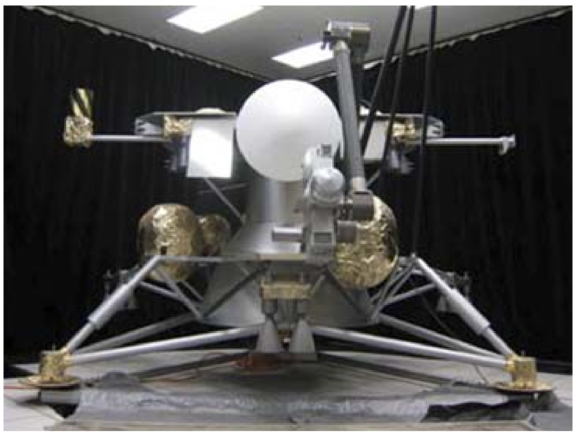

Figure 4: The Moonrise testbed, with sampling arm in center foreground, above the sample pit at the bottom edge of the image.

1.3.4 Mars Seismometry

In 2012 there has been a Discovery mission proposal cycle with the review board site visits recently completed. JPL's participation has been through the InSight mission proposal, which describes a plan to place a lander with seismometer and heat transport probe on the surface of Mars [8]. These instruments require a robotic arm to move them from the lander top deck to the planetary surface. JPL Robotics engineers created a lander testbed and demonstrated the instrument deployment recently.

2. TECHNOLOGY MATURATION

Often there are specified science and program objectives before there is a project funded to attain them – for instance, objectives in Planetary Science have been detailed in the 2011 National Research Council Decadal Survey [9]. Also, it is prudent to address some of the technical issues before any project is created. Such efforts can refine the option space for future missions, while retiring some of the risk. To this end, JPL Robotics is performing concept development and technology maturation for *in situ* exploration of Mars and Primitive Bodies. Additionally, we contribute to similar technology development for NASA's Human Exploration Program, through partnership with other NASA Centers.

2.1 Robotics Technology for Mars

The Decadal Survey has outlined the importance of sample return from Mars. Two important robotic technologies are needed beyond existing rover capabilities: sampling with caching, and fast rover traverse. Additionally, two other technologies promise to increase access to rough terrains containing samples of interest: combined analysis of EDL with roving, and steep terrain roving.

2.1.1 Mars Sampling Technology

Technology for sampling with caching has been investigated for several years resulting in a scalable architecture, prototyped hardware, coring drill control algorithms, and sample tube sealing approaches [10]. The resultant design has four important features. First, there is fusion of visual position estimation and force control to compensate for lateral slip of the rover during drilling, while maintaining weight on bit. Second, sealable cache tubes are inserted in the corer before sampling to capture the sample and enable subsequent transfer and sealing. Third, there is separation of the coring and caching mechanisms by an internal sample transfer arm that allows for optimal cache orientation for system packaging. Fourth, cache canisters are scalable in size and number to enable a variety of rover system sizes and configurations. Fig. 5 shows a prototype system that encompasses these advances.

2.1.2 Rover Fast Traverse Technology

The second area of Mars robotics technology, fast traverse, is necessary to enable relatively quick access to sampling sites in geologically interesting areas that are outside of the landing system error ellipse (which is on the order of 10 km distance with anticipated EDL technology). Increasing the rover's average speed without increasing power consumption requires more rapid processing of imagery necessary for driving decisions and position estimation. This is being accomplished through the migration of flight proven algorithms, GESTALT and Visual Odometry (VO) position estimation, into a field programmable gate array (FPGA) which is very low power with high computational throughput [11].

Figure 5: The JPL Integrated Sample Acquisition and Caching Prototype System.

2.1.3 EDL and Roving Analysis

Current Mars missions treat the analysis of EDL and roving as two separate problems. This has been appropriate since the landing error ellipse has been relatively large (10's of km) and the required roving distances an order of magnitude less. But as new technology decreases the former and increases the latter, it is logical to consider both capabilities in combination during mission planning. To this end, the Combined EDL-Mobility Analysis Trade Study Tool (CEMAT) has been created [12]. CEMAT treats all elements (landing, roving, and terrain knowledge) in a probabilistic framework to understand the costs and trades for attaining access to multiple sampling sites in widely varying terrain on Mars.

2.1.4 Steep Terrain Access

One of the major terrain restrictions for both EDL and conventional roving is the terrain steepness. Large portions of Mars have steep slopes due to cratering and erosion, and are of great scientific interest. Revealed rock layers contain geological history, and apparent water seepage on slopes seen from orbit may provide a habitat for life. Current systems cannot reach these sites for direct measurements, so JPL Robotics is developing a new prototype rover for this purpose. The Axel rover is a tethered two-wheeled system that can be deployed down steep terrain including cliffs, and be returned safely to the starting location at the top [13]. It can be deployed from a larger rover, a precision-guided lander, or as part of a tandem system ('DuAxel') comprised of two Axel robots and a central body, as shown in Fig. 6. Field trials of the prototype have shown the efficacy of this design, and autonomous controls are under development.

Figure 6: The Axel robot separates from the DuAxel system and drops over a cliff edge while supported by a cable.

2.2 Robotics Technology for Primitive Bodies

The Decadal Survey has also called out Primitive Bodies (e.g. comets and asteroids) as targets of strong interest. Therefore, JPL Robotics has been exploring several different system concepts for access to these micro-gravity environments with widely varying surface composition.

First is the All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE), a large vehicle with six 6-DOF limbs with wheels, arranged in a radial pattern. Initial development of this system was for NASA's Constellation Program, with the target application being lunar traverse. However, the flexibility of the design has allowed it to be adopted for micro-gravity interaction with primitive bodies [14]. An inverted Stewart platform has been built with cables to off-load the weight of the vehicle and enable demonstration of landing and hopping, as shown in Fig. 7.

Figure 7: The ATHLETE low gravity testbed uses cables and winches to form an inverted Stewart platform from which the vehicle is suspended.

Second, the Limbed Excursion Mechanical Utility Robot (LEMUR) IIB, a small vehicle with four 4-DOF limbs, has been retrofitted with spiny feet to enable attachment to hard surfaces such as rock or ice [15]. Each foot of this system has a radial array of "toes" that has an array of hooks. The hooks are connected to a central actuator via tendons, and are effective at grasping a rough surface such as vesicular basalt. Fig. 8 shows a testbed for current efforts to use these feet in controlled walking from an inverted surface.

Third, a spacecraft/rover hybrid is being developed in conjunction with Stanford University [16]. This effort uses reaction wheels to affect rolling, tumbling and hopping maneuvers to provide mobility in microgravity. Spikes emanating from the central body of the spacecraft provide lever arms, traction, and compliance for mobility.

2.4 Robotics Technology for Human Exploration

After the termination of the Constellation Program for return to the Moon, NASA has retargeted the Human Exploration Program toward Near Earth Objects (NEOs), primarily asteroids. The ATHLETE system described above is being developed for this purpose, and its large size is appropriate for human exploration. Additionally, JPL is working with NASA Johnson Space Center to develop two other technologies.

First, JPL is creating a prototype grappling arm for the Multi-Mission Space Exploration Vehicle (MMSEV). In the flight version, this astronaut transport system will have three arms which must be capable of final deceleration of the MMSEV, and anchoring to the surface of an asteroid.

Second, JPL Robotics is working with JSC Mission

Figure 8: The LEMUR IIB robot with spiny feet in a testbed to develop walking with gripping on a rough rock surface.

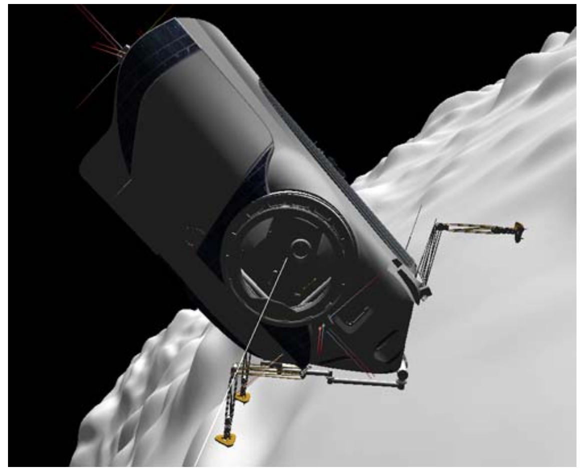

Figure 9: A graphical representation of physics-based simulation of the MMSEV near a NEO. Also shown are the grappling arms, which will be prototyped in hardware as well.

Operations Directorate (MOD) to provide high-fidelity physics-based modelling and simulation using our Dynamics and Real Time Simulation (DARTS) software system [18]. This effort will provide software for Core Operations, Mission Planning, and Analysis Spacecraft Simulation (COMPASS). An initial effort has provided modelling and simulation of the MMSEV operating near a NEO, as depicted in Fig. 9.

3. ROBOTICS RESEARCH

In addition to research directly targeted to NASA problems, JPL Robotics develops solutions to terrestrial problems where the underlying technology will have future applicability to NASA. Often this research is performed for the U.S. Department of Defense (DoD), including the Defense Advanced Research Projects Agency (DARPA), Office of Naval Research (ONR), Army Research Laboratory (ARL), and Air Force Research Laboratory (AFRL). The diversity of the efforts mirrors the diversity of the sponsors' areas of interest.

3.1 Manipulation

Over a decade ago, NASA funded JPL and other Centers to develop technologies in the area of dexterous manipulation for space applications. But during the last decade emphasis has shifted to mobility. JPL Robotics continued to provide manipulation capability for planetary missions, but research in dexterous manipulation had been dormant. With the start of the DARPA Autonomous Manipulation Software Program (ARM-S), JPL has demonstrated its ability to leverage its past strength, and achieved first place standing out of six competitors in the Phase 1 competition. Phase 1 of ARM-S required development of algorithms and

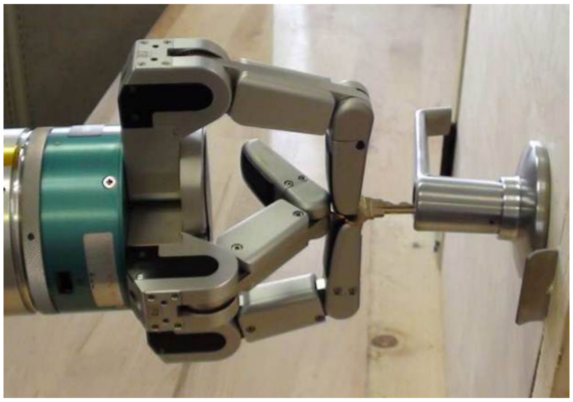

Figure 10: Successful autonomous key insertion and door unlocking as part of ARM-S Phase 1.

software for perceiving and grasping manmade objects in a structured environment. Both the robot system and the environment with objects were provided by the sponsor and consistent across all research teams. Fig. 10 shows one highlight of the JPL effort: the successful autonomous unlocking of a door with compliant control of key insertion [18]. Since the keyhole size is below the resolution of the imaging system, its location is inferred through a series of planned touches and an *a priori* model of the handle.

3.2 Ground Mobility

Complementing and forging new capabilities for planetary mobility, JPL conducts Unmanned Ground Vehicle (UGV) research for ARL and other sponsors. Current research includes development of low cost sensor fusion for all-terrain driving, night time stereo and localization, multi-terrain mobility and path planning, and autonomous stair climbing. Additionally, JPL is one of several subcontractors to Boston Dynamics to develop for DARPA the Legged Squad Support System (LS3) – JPL is responsible for: pose estimation from VO, leg odometry, and inertial measurements; near field mapping (<5m); and night-time illuminators. Finally, JPL is developing a new mobile robot that is very small but can scale obstacles such as steps and walls through the use of hooks embedded in its wheels [19]. Fig. 11 shows this new system, the Durable Reconnaissance and Observation Platform (DROP).

3.3 Sea Mobility

JPL Robotics has extended capabilities for ground vehicles to applications on and under the water. Funded by the U.S. Navy, JPL Robotics has leveraged and extended capabilities in stereo vision, position estimation, path planning, and mission planning for both Unmanned Sea Surface Vehicles (USSV), and Unmanned Underwater Vehicles (UUV). For USSVs, we have demonstrated autonomous control of a small rapidly moving boat amongst several others in random driving patterns. Employed technologies include: wide baseline stereo to sense the moving obstacles, dynamic obstacle avoidance planning, path planning with encoded International Regulations for Preventing Collisions at Sea (COLREGS) to select safe trajectories, and autonomous execution of trajectories with continuous monitoring and replanning [20]. For UUVs, JPL has implemented onboard mission planning to perform simulated adaptive area mine survey operations with hazard avoidance and energy management [21].

3.4 Aerial Mobility and Imaging

In addition to ground and sea mobility, JPL Robotics is investigating aerial mobility and its uses for imaging. Recent efforts with autonomous blimp control have addressed space applications, specifically exploration in the atmosphere of Saturn’s moon Titan [22]. But application to terrestrial, especially DoD, scenarios has been in the domain of small heavier-than-air craft such as quadrotors helicopters. JPL efforts with quadrotor control have concentrated on using visual techniques to enable terrain interpretation and automated landing [23]. Figure 12 shows the scenario and image interpretation used for automated landing on an elevated platform. This effort complements similar space research for advanced EDL, but also lends itself to DoD applications such as landing on moving ships for automated transport, or the edge of rooftops for surveillance. Similar to modelling a landing zone, other structure-from-motion techniques are also being developed for 3D modelling of areas of interest when viewed from greater altitudes by a moving airplane.

3.5 Simulation

As mentioned earlier, JPL Robotics is employing simulation for flight projects and technology

Figure 11: The D.R.O.P. mobile robot, with hooks in its wheels that enable climbing up vertical surfaces.

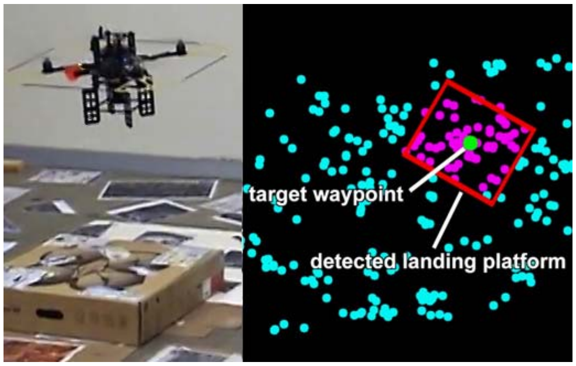

Figure 12: A camera images the floor and box from the moving quadrotor helicopter, allowing determination of range data and extraction of the elevated landing zone. Automated landing follows.

maturation. A common software framework and scripting environment, DARTS/ Dshell, is used. It has its underpinnings in a mathematically rigorous and algorithmically efficient formulation, called Spatial Operator Algebra (SOA) [24]. This combination of DARTS/Dshell and SOA is extremely powerful and flexible, and allows the same core infrastructure to address a wide variety of problems including: spacecraft dynamics with fuel slosh, spacecraft EDL, lighter than air blimps and buoyant submersibles, roving vehicles on soft and rocky terrain, manipulation including ARM-S, and even molecular dynamics for protein folding research. Complementary software packages have also been developed to work with this core: SimScape to provide terrain modelling from planetary to robot scales, and Dspace high fidelity visualization. Currently, granular media simulation is under development.

4. SUMMARY

This paper has briefly described many highlights from the full spectrum of activities being pursued by JPL Robotics. The span of this work stretches from space flight implementation, to directed research for future projects, to more basic research initially directed at terrestrial applications. These efforts involve analysis, design, and implementation of hardware and software, with subsequent laboratory experimentation and field deployment. Future endeavours will strive to maintain or extend this diversity, while infusing new robotic capabilities into space exploration systems.

5. ACKNOWLEDGEMENT

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