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Recent Robotics Developments at NASA/JPL

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1. Introduction

While progress in AI, Robotics and Automation has been achieved in the United States along multiple fronts, this report will focus on JPL contributions to NASA space exploration objectives. Complementary contributions from NASA and university partners are also noted. As an overview, this article will only briefly describe these activities, and detailed descriptions can be obtained both from the i-SAIRAS '08 proceedings, as well as other publications.

This overview will first present relevant technologies from recent and upcoming Mars Missions, including the ongoing Mars Exploration Rovers (MER) mission, the recent Phoenix Mars Lander mission, and the upcoming 2011 Mars Science Laboratory (MSL) rover mission.

Second, this overview will discuss major robotic software systems' technology development, including the Couple Layer Architecture for Robotic Autonomy (CLARAty), the Dynamics and Real-Time Systems simulation (DARTS), the Maestro Operations Interface, and initial efforts to combine these.

Third, the overview will describe recent efforts in exploration technology development as targeted to three planetary mission scenarios: Mars, Lunar, and atmospheric (Venus and Titan).

Fourth, major recent astrobiology technology research is described, and a summary is provided.

2. Mars Flight Robotics Progress

Launched in 2003, the MER rovers, Spirit and Opportunity, have continued to operate on the Martian surface well beyond their target lifetimes. Not only has this allowed for a significant expansion of their original science objectives, but has also provided the chance to thoroughly exercise the robotics systems, both in their original form, and as enhanced by subsequent software upgrades.

As originally flown, the spacecraft functionality included: lander descent image motion estimation (DIMES), image feature tracking for visual odometry, stereo vision for obstacle detection, local path planning for obstacle avoidance (GESTALT), vehicle kinematics and control for driving, and manipulator kinematics and control for instrument placement. This onboard software suite was originally limited due to project development schedule and flight system limitations, including the 20 [MHz] flight processor. Additionally, ground control software with robotics heritage included the two primary operations interfaces: RSVP for engineering, and Maestro for science.

However, with the longevity of the flight system, and technology development funding from the Mars Technology Program, several additional capabilities were matured, validated, and transferred to the flight system. These include: visual target tracking for autonomous instrument placement (VTT), model and vision based manipulator collision prevention, global path planning (Carnegie Mellon's Field D*, see **Fig. 1**), and image processing for autonomous dust-devil detection. All have been exercised on the flight systems on Mars. Usage of any algorithm, original or added, is at the discretion of mission planners according to the requirements of the activities for any specific day.

In 2008, the rovers were joined on Mars for four months by the Phoenix lander, which touched down north of the arctic circle on Mars, and survived through the Martian summer. While Phoenix was a static lander, it employed some of the same technology used by MER. First and foremost, the manipulator on Phoenix

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Fig. 1 MER Opportunity tracks made while driving with GESTALT and D*

was crucial for sample acquisition and delivery to the science instruments on the top of the spacecraft. JPL robotics led the development, implementation and operations for manipulator control for constrained motion while digging, grinding, and scraping, and precision placement during sample delivery. Additionally, robotics technologies were employed for operations (adapted versions of MER's operator interfaces, RSVP and Maestro); physics-based simulation of entry, descent and landing (EDL) for mission planning; and image processing of orbital imagery for landing site selection.

Planned for 2011 is the next rover mission, the Mars Science Laboratory (MSL). MSL is roughly twice as big as MER in all dimensions, and approximately five times more massive. This allows for a larger science payload, and carrying of a nuclear power source (RTG). Without solar panels to become dust-covered, and with the constant heat from the RTG, MSL will not suffer the same thermal and power cycling problems that contributed to the conservative lifetime predictions for MER—instead its primary mission is one full Martian year. Its robotic capabilities will include all those available for MER, plus manipulator-based drilling to acquire rock samples. As was enabled by the longevity of MER, it is anticipated that future software upgrades will add functionality to the rover.

3. Robotics Software Technology

To support technology development such as that successfully employed for MER, the Mars Technology Program has funded several forms of software infrastructure for onboard control, physics-based simulation, and ground control operations.

CLARAty has been developed to provide a common software infrastructure for robot control. It consists of two layers. The Functional Layer is an object-oriented framework for defining the relationship between all components of robot control, while providing support for heterogeneous robots, and complementary or competitive algorithms. The Decision Layer contains deliberative planning and scheduling as well as execution, and has a defined interface for accessing the Functional Layer capabilities at different levels of abstraction. CLARAty development has been a cooperative effort with NASA JPL, NASA Ames, Carnegie Mellon University (CMU), and the University of Minnesota. Algorithm development from these institutions, as well as others such as MIT, have been captured in the framework.

DARTS is a physics-based simulation system which has been developed for emulation, controls, mission planning, and operations. While original versions of the system were used for free-flying spacecraft, recent missions have required simulation of in-situ situations—these included entry, descent, and landing; surface roving; or aerial operations. Models developed for EDL have been developed and used in a software deployment named DSENDS. Additionally, DSENDS can be used for aerial robot (aerobot) simulations. Models for surface wheel-terrain interaction have been coupled with terrain models and data in another software deployment named ROAMS. Both DSENDS and ROAMS are used for technology development for Mars, Moon, and Titan, and missions such as Phoenix and MSL.

Maestro is a Java software system for user interfacing during mission operations or technology development. It has been used for rover and aerobot field testing; MER and Phoenix missions, and is planned for use in MSL. Its component architecture, allows for contributions from several organizations, including NASA Ames.

Recent efforts have combined CLARAty, ROAMS, and Maestro into an end-to-end simulation of a full mission. Such a combined system has value as a "flight simulator" for operators and scientists to train for future missions, and as a mechanism by which to test technology components in a full system. For instance, new autonomy technology can be more easily integrated, and feedback on its utility can be obtained.

4. Planetary Robotics Applications

In addition to development of software systems, component technologies are under development for Mars, Moon, and extraterrestrial atmospheric exploration.

For Mars, autonomy needs can be divided in four categories: long traverse, instrument placement, onboard science data processing, and sampling. For long traverse, mobility on steep terrain may require tethered systems, therefore JPL is investigating design and control of such systems (e.g. Cliffbot and Axel). For instrument placement and onboard science, JPL is developing autonomous visual rock detection and instrument pointing (OASIS). For sampling, JPL is investigating autonomous rock coring and caching from a MER class rover. Some of these may mature quickly enough for eventual use on MSL. Others may only be suitable for future missions such as a possible sample caching mission in 2018.

The NASA Exploration Systems Mission Director (ESMD) has a strong program to develop all the needed systems for a return to the Moon. Two major components of the program architecture are mobile assets for the lunar surface: small pressurized rovers being developed by NASA JSC (Chariot), and larger mobile habitats based on JPL's ATHLETE system (shown in **Fig. 2**). ATHLETE is a six-limbed system, where each limb has 6 degrees-of-freedom (DoFs), plus a wheel. With a total of 42 DoFs; ATHLETE can carry and dock payloads, carry and employ tools for grasping, digging, and drilling; and drive or walk over rough terrain while actively controlling its attitude. Walking algorithms for ATHLETE are under development by NASA Ames, and operations of the system are performed using modified versions of the RSVP and Maestro interfaces from the Mars program. Several field tests of ATHLETE have been performed, both alone and in conjuction with other systems, such as JSC's Chariot.

Fig. 2 NASA JPL ATHLETE

Fig. 3 NASA JPL Titan Aerobot Testbed

Finally, for planned future missions to planetary atmospheres, JPL is developing several different aerobot designs. Pressurized balloons are under development for Venus applications, where the upper atmosphere is cool enough to permit conventional spacecraft design for the payload. Challenges for this mission scenario are primarily materials technology for the caustic atmosphere. Similar, unpressurized Montgolfier designs are also under development for Titan. Using solar or RTG heating, and changing altitude to catch changing wind directions, some level of navigation is possible. Additionally, JPL is studying fully controlled blimps for autonomous exploration of Titan (as shown in **Fig. 3**). Earth tests of these systems have shown the ability to determine position with ground feature tracking, executing desired altitude and course corrections to loiter near science targets, and drop sample capturing tubes with tethered retrieval.

5. Other Developments

In addition to the Mars and ESMD programs described above, NASA also provides funding to scientist-led teams through the ASTEP astrobiology program. Within this program and related funding, CMU has researched topics such as performing spectroscopy on rover platforms, plowing as a mobility concept for steep crater walls, field testing to simulate search for life in the Atacama Desert, autonomous mapping at kilometer scales, and designing a rover concept for the lunar polar cold traps. The most compelling of these recent CMU efforts is the DEPTHX underwater autonomous vehicle, which successfully explored the world's deepest cenote (sinkhole) in Zacaton, Mexico. For the excellence and range of his research and results, Dr. David Wettergreen received the i-SAIRAS '08 award for Most Outstanding Contribution to the Technical Program.

6. Summary

This article has provided a brief overview of NASA related space robotics efforts in the US. Much of the technology and mission implementation described is from NASA JPL, given its prominent role in Mars exploration, and long history in space system development. Also, key collaborations with other institutions such as JSC, Ames, and CMU are also described. In addition to Mars exploration, relevant progress in lunar, aerial, and astrobiology technology has been discussed.

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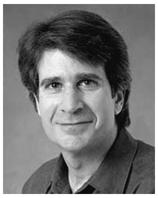

Richard Volpe

Dr. Richard Volpe is Manager of the Mobility and Robotic Systems Section of the Jet Propulsion Laboratory, NASA/Caltech. The section is a team of over 80 robotics engineers doing research and spaceflight implementation of robotic systems for roving, digging, ballooning, drilling, and other modes of in-situ planetary exploration. Richard is also a member of JPL's Science and Technology Management Committee (STMC), and has been a member of the Phoenix Mars Lander Robotic Arm team. From 2001 through 2004, Richard served as the manager of Mars Regional Mobility and Subsurface Access in JPL's Space Exploration Technology Program Office. In addition to guiding technology development for future robotic exploration of Mars and the Moon, he has been actively involved in 2003 & 2011 rover mission development. This has included managing internal JPL rover technology development, as well as external university research funded by the Mars Technology Program. Richard holds a PhD in Applied Physics from Carnegie Mellon University.

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Mr. Richard Doyle is Manager of the Mission Software, Computing, and Networking Program Office at the Jet Propulsion Laboratory, California Institute of Technology in Pasadena, California. He is an advisory board member at IEEE Intelligent Systems, where he contributes the department "AI in Space." He served as a member of the Executive Council of the Association for the Advancement of Artificial Intelligence (AAAI) during the period 2000–2003. He is an Associate Fellow of the American Institute of Aeronautics and Astronautics (AIAA). Dr. Doyle is a recipient of the NASA Exceptional Service Medal. He holds the Ph.D. in Computer Science from the MIT Artificial Intelligence Laboratory. He gave the invited talk entitled "The Emergence of Spacecraft Autonomy" at AAAI-97 in Providence, RI. He has been the US Program Chair for the International Symposium on Artificial Intelligence, Robotics and Automation in Space (i-SAIRAS), held at Tokyo in 1997, Noordvijk, The Netherlands in 1999, Montreal, Canada in 2001, Nara, Japan in 2003, and Munich, Germany in 2005. He was General Chair for the i-SAIRAS held at University City, Los Angeles in 2007. He is Local Arrangements Chair for the International Joint Conference on Artificial Intelligence (IJCAI-09) to be held in Pasadena, California in July 2009.