2014 Robotics Activities at JPL

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Abstract

A broad spectrum of robotics research and space robotics implementation is being conducted at the Jet Propulsion Laboratory (JPL), California Institute of Technology (Caltech). Central to these activities is the engineering staff of the Mobility and Robotic Systems Section (also known as JPL Robotics). This paper will describe these activities, from flight implementation and operations, to NASA funded technology maturation, to non-NASA funded research for terrestrial applications.

1 Introduction

While every spacecraft might be considered to be a robot, JPL Robotics concentrates on development of systems for in-situ operation and exploration. For planetary missions, the primary focus has been on mobility and manipulation, but airships continue to be proposed for flight project implementation. To support and feed into these flight projects, two types of research are conducted: NASA-funded mission-focused technology development, and non-NASA-funded applied and basic research on terrestrial applications. This paper will describe on-going JPL Robotics activities in all of these areas.

2 Flight Projects

Currently, JPL Robotics is involved in a variety of major flight projects, including: operations of two Mars rovers exploring the surface, the completion of a new lander for sub-surface science, the initial development of a new rover for sampling, the investigation of new mission concepts for asteroid retrieval, space station operations software support, and a proposal for a small Mars helicopter. This section will describe ongoing contributions to these efforts in more detail.

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2.1 Mars Exploration Rovers (MER)

At the time of this writing, the one operational MER rover, Opportunity, has been exploring Mars for over 3600 sols (Mars' days) and has traversed about 39 km. While currently in the middle of the Mars winter, power levels are relatively strong due to wind cleaning of the solar arrays. The rover is still exploring the western edge of the large Endeavour crater, examining rock outcrops, layering, and interesting geologic specimens such as the recent "jelly donut" rock. JPL roboticists serve as rover drivers and operations specialists for this mission, with recently added personnel being trained for these roles as well.

2.2 Mars Science Laboratory (MSL)

At the time of this writing, the MSL rover, Curiosity, has been exploring the terrain of Gale crater for over 600 sols, traversing about 6.3 km. The recent arrival at a major waypoint named "The Kimberly", brings an operational transition from sols of driving to those of sampling – drilling into selected rocks to obtain rock dust for deposition into onboard scientific analysis systems.

One recent challenge experienced by the system was encountering terrain with extremely sharp rocks which damaged the wheels at a rate and fashion not anticipated. The issue has been addressed through modified driving techniques, careful selection of traverse routes, and on-going analysis with the Vehicle System Test Bed (VSTB) in the JPL MarsYard. Due to the caution induced by this experience, use of rover autonomous navigation has been limited to date [1].

JPL Robotics personnel have been heavily involved in aspects of Curiosity development and operations. Currently, members participate as analysts of telemetry, rover planners for both driving and manipulation operations, verification and validation for system performance, and software upgrades. Some personnel have transitioned, or will be transitioning, to the Mars 2020 project described below. A new "class" of robotics engineers has been selected and is now in training to serve as replacements for those transitioning to the new rover project.

2.3 InSight

The InSight Mission will place a lander on the surface of Mars in September 2016. The landing system is the same as type as used on the Phoenix mission in 2008, and both spacecraft have a similar appearance due to the solar panels and robotic arm on each. But contrary to Phoenix which employed digging and delivery of samples to fixed instruments on the lander top-deck, Insight will use the arm to deploy instruments to Martian terrain.

The primary science instruments on InSight are the Seismometer Experiment for Interior Structure (SEIS), the Heat Flow and Physical Properties Package (HP3), and Rotation and Interior Structure Experiment (RISE). Whereas RISE is radio fixed to the lander, SEIS and HP3 must be deployed to the surface of Mars. Instrument placement will be done by the Instrument Deployment Arm (IDA), which will also deploy a Wind and Thermal Shield (WTS) cover over the SEIS instrument, as shown in Figure 1. The instrument deployment to the surface is made challenging by a number of factors including: limited Mars surface workspace accessible by the IDA, the relatively large footprint of the instruments, rock abundance on the surface and potentially below it (since the HP3 has a thermal probe that must burrow below the surface on which it is placed), and tethers connecting the instruments to the lander.

Project cost constraints have dictated the inheritance of existing manipulator hardware from the cancelled Mars 2001 mission [2]. This arm has effectively 3 degrees of freedom (DOFs), to which has been added a grapple mechanism hanging from a short, flexible cable. While this arrangement has the advantages of simplicity and passive compliance, it also introduces uncontrolled DOFs, primarily about the gravity vector, allowing yaw of the instruments during deployment. This yaw is constrained and countered by the tethers, but greatly enlarges the possible footprint that must be considered during planning for placement.

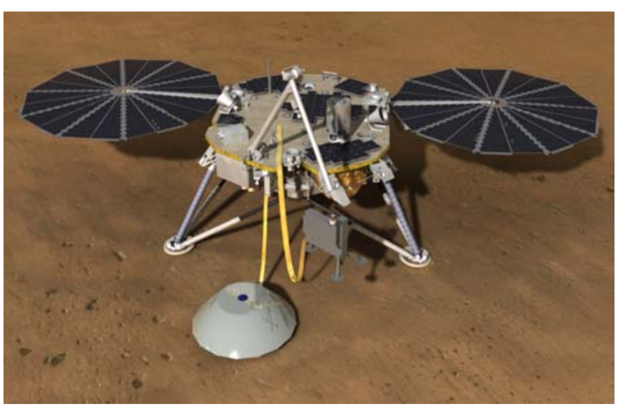

Figure 1: Artist's rendering of the Insight lander on the surface of Mars. The IDA is shown deploying the HP3, while the SEIS is already deployed and covered by the WTS.

JPL Robotics personnel are leading the IDA subsystem, providing the control software for the arm, and developing the manipulation test bed and verification and validation of deployment activities. Also, to facilitate IDA operations on the surface, an adaptation of the Robot Sequencing and Visualization Program (RSVP) is being prepared by JPL Robotics personnel [3]. This software package has been used on the MER and MSL rover missions, as well as the Phoenix lander mission. It provides 3D visualization based on models and telemetry for evaluating state and simulating actions, as well as interface to build and evaluate command sequences for uplink.

2.4 Mars 2020 Rover

The next rover mission being planned would launch in 2020 and perform rock sampling and caching for possible later retrieval by follow-on missions. The current concept being developed is primarily a build-to-print copy of the MSL rover, with selected modifications to accommodate a different science payload suite, currently being selected through a proposal process. Since the sampling objectives are specified for the mission, new hardware will need to be added for rock coring and caching operations, and this is likely to lead to a new manipulator design as well. JPL Robotics personnel have been leading the development of the architecture for coring, sample tube sealing, and sample caching for several years, and this technology is under evaluation by the project [4][5].

Another improvement under consideration for this rover system is the addition of field programmable gate array (FPGA) electronics which would enable fast image processing for use during landing and roving. JPL Robotics personnel have been participating in Entry, Descent, and Landing (EDL) technology development of the Lander Vision System (LVS) for terrain relative navigation and hazard detection [6], as well as complementary use of the same FPGA hardware for fast rover traverse with stereo vision and visual odometry [7].

2.5 Asteroid Redirect Robotic Mission

NASA's Asteroid Redirect Robotic Mission (ARRM) is a concept currently under development which would capture an asteroid and place it in orbit around the Moon for later rendezvous and study by astronauts [8]. JPL Robotics is involved in several aspects of this mission concept development. First, the Dynamics and Real-time Simulation (DARTS) software system has been employed to implement mathematical models to provide an accurate, physics-based preview of

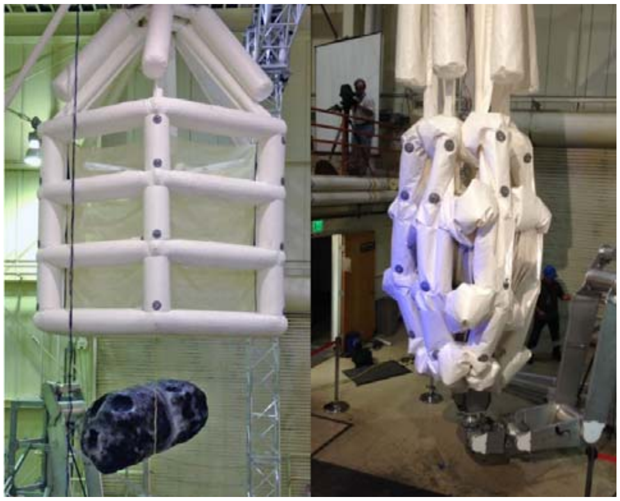

Figure 2: The ARRM asteroid capture testbed, showing before and after a demonstration of the inflatable system. On the left the asteroid (below) is being approached, and on the right the asteroid has been captured and the system is deflated and constricted to hold it.

the proposed concept, showing its viability [9]. Second, a physical test bed of a prototype inflatable capture system has been built and demonstrated, as shown in Figure 2. While this primary concept envisions capturing an entire small asteroid in a "bag", an alternative concept has also be explored where a boulder would be grabbed off the surface of a large asteroid. JPL Robotics has developed a key technology to enable this alternative concept – microspine grippers which use arrays of hooks in a compliant radial structure which can grasp the rough surface of a rock [10][11].

2.6 COMPASS

The DARTS software has also been selected by the NASA Johnson Space Center Mission Operations Directorate (JSC-MOD) as the foundation for a new simulation environment – Core Operations, Mission Planning and Analysis Spacecraft Simulation (COMPASS) [12]. In collaboration with JSC-MOD, JPL Robotics personnel have been working to build and extend models and software for use in ascent, descent, rendezvous, and proximity applications for manned flight missions including the International Space Station (ISS). For example, Figure 3 shows the COMPASS simulation of an approach path for rendezvousing with the ISS.

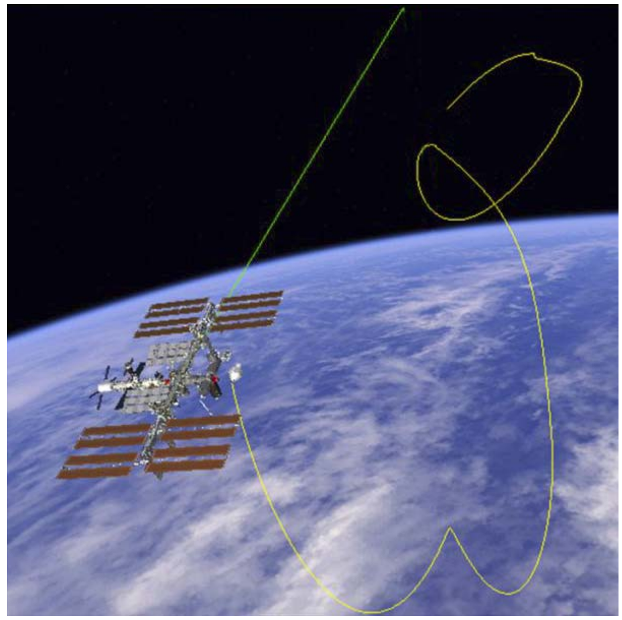

Figure 3: DARTS-based simulation of the approach path for rendezvous with the ISS.

3 Mission Proposals

In the interest of infusing technology and personnel in to flight missions, JPL Robotics participates in a wide variety of mission proposals. Two of the major NASA solicitations are the Discovery and New Frontiers Programs. Currently the Discovery program is in the beginning of a new cycle, with the Announcement of Opportunity due out later this year. Robotics technology is anticipated to be valuable to several concept missions under development, but details cannot be discussed at this time for proprietary reasons. However, it is possible to discuss a recent science payload proposal submitted to the Mars 2020 mission and still under review – the Mars Helicopter Scout.

3.1 Mars 2020 Helicopter Scout

JPL Robotics has led the development of a proposal for a small helicopter to act as a science payload on the Mars 2020 mission. Figure 4 shows an artist's depiction of this system. This aerial system would be deployed by the Mars 2020 rover, and would work in partnership with it. Features of the system include: total mass of 1 kg; counter-rotating propellers designed for use the thin Martian air; powered by solar charged batteries; a high resolution downward looking camera for navigation, landing, and science surveying of the terrain;

Figure 4: Artist's depiction of the proposed Mars 2020 Helicopter Scout.

and a communication system to relay data to the rover.

The operations mode for this helicopter would make it an aerial asset for expanding the exploration of the terrain ahead of the rover, for target selection, path selection, and geologic context. As envisioned, for safety the helicopter would never be directly near the rover. Instead, it would be dropped off on the ground, and only become active after the rover has driven away by a sufficient distance. Further, the communications system would provide the relative positions of the systems to prevent flight paths that might bring the helicopter near the rover. Individual daily flights would be limited to a short duration of approximately 3 minutes due to power, but it should attain ~100m altitude and ~600m ground track. Daily communication of helicopter data will provide overhead image resolution ~10x greater than orbital images, and greater area coverage than can be seen from the rover.

The final verdict on this proposal is due later this year.

4 Robotics Technology Maturation

To open up the possibility of new proposal concepts for the future, and to mature the technology for readiness when future opportunities arise, JPL Robotics is actively developing systems targeted to specific missions. Of particular interest in this set are technologies for steep terrain access, primitive body mobility, and spacecraft surface mobility and manipulation.

4.1 Steep Terrain Access

While the MER and MSL rovers have made great progress in the surface exploration of Mars, they are restricted to slopes less than 30 degrees and typically much less. Since landing systems are also restricted to relatively benign terrain within their error envelop, the mobility systems are consistent with the landing systems in terms of terrain roughness. But interesting steep terrain such as the layered cliffs of Victoria crater observed by Opportunity, would be best explored by a roving system with steep terrain access capabilities. Moreover, as landing system become more accurate and rover system more long range, there will be a need to traverse through rough and steep terrain outside the reduced landing envelope. In particular, exposed stratigraphy in steep terrain, hypothesized seepage events on crater slopes, or skylights of caves and lava tubes which might harbor water ice, are all prime candidates for exploration requiring new mobility systems.

One system under development by JPL Robotics for steep terrain access is the Axel Rover System [13]. In its simplest form, the Axel Rover is a two-wheeled tethered system which can drive up and down very steep terrain, or even be lowered through free air on its cable. Several field tests have shown its ability to be teleoperated up and down rough slopes, although research remains to make such operations fully autonomous with obstacle avoidance and tether management. Additionally, two Axel rovers have been combined with a central payload module to form a DuAxel system, which can traverse as a four-wheeled rover over more level terrain, until steep terrain for exploration is reached, at which time on Axel is separated and egresses down the steep terrain.

As an alternative to tethered wheeled mobility, JPL Robotics is also leveraging the development of microspine gripping technology (discussed earlier for asteroid capture) combined with limbed robots to enable steep or inverted mobility [14]. This concept is unique in its ability to grasp the surface and thereby enable exploration of rock overhangs or cave ceilings, such as might be accessible through the skylight of one of exposed lava tubes seen in orbital imagery.

4.2 Primitive Body Mobility

"Primitive Body" is a generic term for asteroid and comets, which typically have very weak gravity. The same microspine grasping robot described above for steep terrain access is appropriate for grasping these bodies if they have a rocky surface. But for the case

Figure 5: The SmalBoSSE limbed robot in its test bed with active gravity compensation.

where the surface is dust or ice, other techniques are being investigated.

JPL Robotics is developing limbed mobility that does not grasp the surface, but rather employs control algorithms to maintain stability while walking with very low gravity. To this end, the Small Body Surface Sampler and Explorer (SmalBoSSE) robot and gravity off-load test bed have been developed [15], as shown in Figure 5. SmalBosse has shown the viability of statically stable multi-limbed walking in low gravity.

As a simpler alternative to limbed mobility under low gravity, JPL Robotics is also collaborating with Stanford University on the development of a next generation hopping robot called "Hedgehog" [16]. This system is a similar concept to the Japanese Minerva hopper [17], but is extending control and actuation to three degrees of freedom, while changing the design to include long protrusions from the central body to provide longer lever arms for interaction with the terrain. Current Hedgehog research includes both control and path planning algorithms.

4.3 Spacecraft Surface Mobility and Manipulation

In addition to limbed mobility and manipulation for the low gravity natural environment of Small Bodies, JPL Robotics research is also exploring technology to extend these capabilities to manmade environments of spacecraft surfaces such as the International Space Station (ISS). Central to this effort is the development "gecko skin" fibrillar adhesives that use microscopic hair-like structures which bend under shear loads to create greater contact surface area which electrostatically adheres to the environmental surface through Van der Waals forces [18]. End-effectors are being developed to use this material for grasping smooth surfaces on the inside and outside of spacecraft, to enable a wide variety of applications from inspection to orbital debris capture. Currently under development is a prototype ISS Remote Inspection System (IRIS) robot, which will be a four limbed system designed to walk on an exterior surface while performing visual and contact inspection operations.

5 Robotics Research

To complement the space application technology development, JPL Robotics also has active research in a spectrum of terrestrial robotics, primarily funded by a variety of US Department of Defense (DoD) programs.

5.1 Limbed Manipulation and Mobility

After successful completion as a leading team (with Caltech) in the DARPA Autonomous Robotic Manipulation Software (ARM-S) program [19], JPL Robotics transitioned this software expertise to the DARPA Robotics Challenge (DRC). Originally this software effort was in a different track from JPL's hardware entry for the program, the Robosimian robot with four 7 DOF limbs, shown in Figure 6. With the program manager's approval, these two teams were

Figure 6: The Robosimian robot walking over concrete blocks during the DARPA Robotics Challenge in December 2013.

merged along with collaborators at University of California Santa Barbara (UCSB). During trials in December 2013 in Homestead, Florida, the combined team placed in the top five [20]. Highlights of Robosimian's design are its low cost, mass, and size, and its statically stable configuration with four limbed or four wheeled poses. This was in contrast to most other competitors who employed bipedal humanoid robots for the contest. Current research is preparing the Robosimian system for Phase 2 trails early next year.

This ongoing DRC effort is now being complemented by a new research for the Defense Threat Reduction Agency (DTRA). Initial research has concentrated on reconfiguring portions of the Robosimian design into dual 7 DOF manipulation with a 7 DOF torso and tracked mobile base. The modularity of the design allows for quick consideration of such alternative deployments depending on the objectives at hand.

5.2 Ground Mobility

In addition to limbed manipulation and locomotion, JPL Robotics has a long history of perception and autonomy for autonomous driving in natural terrains. For instance, JPL's research in stereo vision for army vehicles two decades ago helped enable the use of this technique on the Mars rovers.

Current efforts are in a wide variety of topic areas, including: stereo vision bias removal by autocorrelation [21]; sensor fusion for robust perception using lidar, visual, and infrared stereo [22]; low cost stereo vision system designs for nighttime driving using both visual and infrared cameras; High Dynamic Range (HDR) stereo for daytime scenes with deep shadows; localization, mapping, and dynamic obstacle detection with stereo vision for the Boston Dynamics Legged Squad Support System (LS3) [23]; and pedestrian detection, classification, and activity interpretation [24][25].

5.3 Sea Mobility

A logical extension of perception and planning for ground mobility is to do similar for watercraft. JPL Robotics has developed stereo systems to enable visible and infrared wide-baseline, multi-resolution stereo for autonomous driving of boats. The visual system enables detection of static obstacles (e.g. bridges, buoys, etc.) as well as moving obstacle (other boats) at large distances [26]. Additionally, tracked boats and analysis of navigation lights (at night) are used in a path planner that employs the International Regulations for Preventing Collisions at Sea (COLREGS) to generate and execute safe trajectories for the boat [27].

Beyond these basic capabilities for autonomous driving of boats, JPL Robotics has been developing a number of enhancements for long duration sea missions. These include: tactical path planning and onboard health management [28]; 360 degree high resolution viewing in visible and infrared, segmentation and tracking of other boats, and fine grained classification of them [29]; visible and IMU based determination of sea state and navigation planning based on it; and game-theoretic navigation planning in the presence of other adversarial boats.

5.4 Aerial Mobility

The previously discussed Mars Helicopter Scout proposal is partially based on aerial vehicle technology development ongoing in JPL Robotics. Most of this research is concentrating on improving the onboard vision-based control of micro air vehicles. In particular, three specific capabilities are being developed: rooftop detection for edge landing for surveillance [30], position estimation through fusion of optical flow and inertial measurements to provide drift free navigation and basic aerial system safing [31], and side-looking stereo vision for obstacle avoidance while flying in cluttered environments (e.g. between trees, through doorways) [32].

Figure 7 shows data from one test of flying between trees, where data is presented in a plan view showing detected points at least 2.5 m above ground and less than 2m from the quadrotor helicopter test bed. Also shown in the inset is the side view, from behind the vehicle,

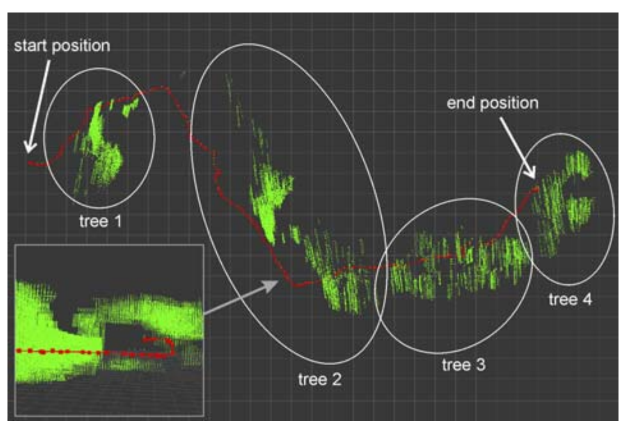

Figure 7: Data from a test of stereo vision based collision avoidance of a quadrotor helicopter flying between trees. See text for details.

illustrating a path autonomously selected to successfully avoid a tree branch.

6 Summary

This paper has presented the broad spectrum of JPL Robotics activities which are ongoing. There are multiple dimensions to these activities: spaceflight implementation to basic research, mechanical engineering to software, sensor processing to controls, and component technology to system integration. The breadth of activities is matched by the depth of completeness in most of these endeavors. It is also anticipated that research efforts have a flow into future space system deployments, contributing to an exciting future for space exploration in the decades ahead.

7 Acknowledgment

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