2018 ROBOTICS ACTIVITIES AT JPL

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ABSTRACT

This paper will provide an overview of current robotics activities at NASA's Jet Propulsion Laboratory (JPL), California Institute of Technology. In addition to reviewing ongoing flight projects, a discussion of significant research efforts is provided. This dual discussion will indicate the technology infusion pathways that enable advancement of robotics capabilities for scientific space exploration.

1 INTRODUCTION

The Robotics Section at the Jet Propulsion Laboratory (JPL Robotics) is a team of 150 engineers addressing a broad set of problems from space flight implementation to basic research. This team is a small subset of the thousands of engineers at JPL, but provides unique capabilities for development of systems for *in situ* robotic exploration. This includes: visual perception of environment structure and properties, mobility in natural terrains, contact operations for instrument placement and sampling, operator interfaces, and modeling and simulation of robots and their surroundings. About half of JPL Robotics is directly supporting spaceflight projects, and the other half is divided between NASA and non-NASA funded robotics research. All research is designed to solve technical problems that will both address immediate research program needs, while also enabling technology infusion into future flight missions. Each of these areas of engineering research and development are covered in the following sections.

2 FLIGHT PROJECTS

Currently, JPL Robotics is directly participating in a set of exciting flight projects, primarily dedicated to Mars exploration. First, personnel serve as the rover drivers for two active rover missions in operation on the surface: Mars Exploration Rover (MER) "Opportunity" [1], and Mars Science Laboratory (MSL) "Curiosity" [2]. Second, the upcoming InSight lander mission [3] has a team of roboticists who have developed a manipulation subsystem which they will control during surface operations next year, to enable seismometer and heat-probe deployment. Third, robotics engineers are heavily involved in two new subsystems on the upcoming Mars 2020 (M2020) mission [4]: sampling and caching, and fast traverse. The sampling and caching subsystem will acquire small cores of rocks and regolith, encapsulate them, and deposit them on the surface. The fast traverse capability will use an FPGA-based vision system to enable more driving each day, allowing access to a greater variety of sites for sampling. This faster mission pace also requires new operations tools which are currently under development. Fourth, JPL robotics personnel have been major contributors to the development of a Mars Helicopter technology demonstration system, which is currently under consideration by NASA as a possible addition to M2020.

2.1 MER and MSL

JPL Robotics personnel are centrally engaged in the ongoing operation of NASA's two active Mars Rovers: Mars Exploration Rover (MER) "Opportunity" and Mars Science Laboratory (MSL) "Curiosity."

Opportunity started its mission in 2004 and has completed over 5000 Martian days (sols) exploring the terrain of Meridiani Planum. For the past six years, this exploration has concentrated on the terrain at the rim of the Endeavour Crater. Originally, the rover (and its duplicate, "Spirit") was designed for only a 90-day mission – and has fortuitously lasted much longer. But as the rover has aged, its operation has presented challenges to robotics engineers, including: intermittent power shortages due to solar panel dust accumulation and sun angle with time of year, survival through the Mars winter, memory hardware failures, steering actuator failure, steep terrain access, etc., as well as departures of operations personnel. Despite these challenges, Opportunity persists.

Curiosity, is roughly four times the size of Opportunity, and powered by a Radioisotope Thermoelectric Generator (RTG) which provides a constant source of electrical and thermal energy. Therefore, this rover was expected to survive at least two years on Mars, but is now in its sixth year exploring Gale crater.

JPL Robotics personnel participated in the design and construction of both of these rovers, including software for control and operation. Lesson learned from Opportunity informed the development of Curiosity, but unique challenges have also been addressed for it. Some of these challenges and solutions for Curiosity have been: incorporation of variable drive modes that employ features such as visual odometry [5] or global path planning at the discretion of the operators; a new algorithm for improving traction control and reducing unexpected wheel wear [6]; and new operations modes for carrying soil samples while driving, or self-inspection of the vehicle. These developments and other lessons are guiding the development of the Mars 2020 rover, discussed later in this paper.

2.2. INSIGHT

At the time of this writing, the InSight Mars lander mission is about to launch from California. JPL Robotics personnel are responsible for the delivery and operation of the manipulator, named the Instrument Deployment Arm (IDA), which will deploy two key science instruments to the surface – a seismometer from France, and heat probe from Germany. Figure 1 shows laboratory tests of this deployment process. The team has leveraged controls software, operations tools, and personnel expertise from the 2008 Phoenix Mars Lander Mission. Interestingly, due to reuse of legacy hardware by InSight, its manipulator also has a digging scoop like Phoenix – but primary mission plans do not call for its use. Unlike Phoenix, the camera on the Insight arm is the only one available for stereo imaging of the surrounding workspace terrain, so the robotics team is also responsible for these image sequences as well.

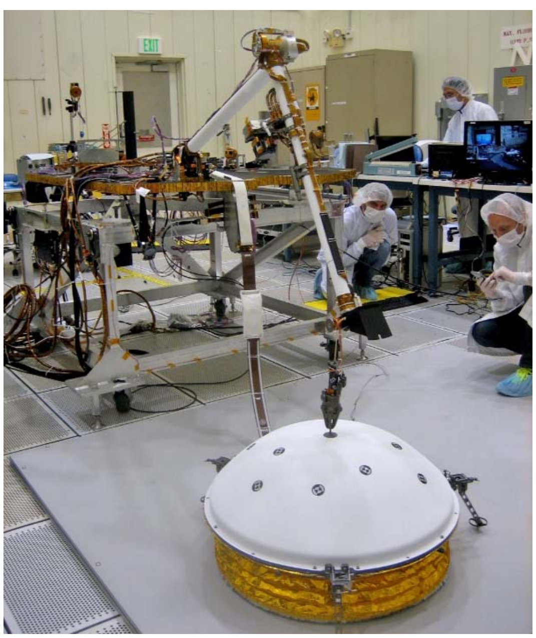

Figure 1: Laboratory tests of the InSight Instrument Deployment Arm lowering the seismometer cover to the ground.

2.3. M2020

The Mars 2020 Rover Mission (M2020) is largely a build-to-print duplicate of the MSL Curiosity rover, with some key upgrades for improved operations, improved mobility, and sample acquisition and caching. JPL robotics personnel are participating in, or leading the development of these new capabilities, as described below:

Improved Operations: Since M2020 is a sample collection rover, there is a science requirement to collect these samples from a geologically diverse set of locations. This places requirements for a faster mission tempo, both for operations and rover mobility. For operations, nominally all planning and sequencing will be completed in five hours. This requires new capabilities in the operations tools to enable situational awareness, integration of science intent with engineering expertise, improved interfaces for rover motion constraints and commanding, as well as leveraging of pre-validated sets of activities.

Improved Mobility: The primary enhancement that will enable increased mobility for M2020 is the addition of an FPGA image coprocessor. This drastically increases the speed of computation for stereo vision and visual odometry, allowing their results to be computed while the rover is executing its last commanded arc of motion (usually a one meter move). Not only does this enable the average speed of rover motion to be greatly increased, but it is safer due to higher resolution processing of the stereo data, and visual odometry providing a check for rover sinkage or slippage in the terrain. Additionally, to take full advantage of this new processing capability, the local path planner is being upgraded to incorporate a more detailed rover model, enabling the planning of paths in terrain with greater obstacle density, including straddling low rocks if necessary and possible.

Also part of the improved mobility is a new wheel design that should eliminate the wear seen on MSL wheels. To complement these new wheels, M2020 will also use the MSL traction control algorithm.

Sample Acquisition and Caching: The architecture for sampling and caching was developed by JPL Robotics prior to M2020 [7]. In this architecture, the primary manipulator on the rover uses a coring drill to obtain rock samples (approximately 1cm x 5cm in size) and secondary manipulator positions them for sealing in a metal tube. These tubes can then be carried along with the rover or deposited on the surface at the discretion of scientists and operators.

For flight project implementation, the mechanical design is largely being led by other parts of JPL or private companies, with Robotics personnel participating in the oversight and management of those efforts. Complementing the hardware efforts are software development, verification and validation, and sampling operations – all of which are the direct responsibility of JPL robotics personnel. It is important to note that the current plan for M2020 is to employ an "adaptive caching" strategy, where the sample tubes are deposited on the surface at selected depots. This could allow a potential future mission with a Sample Retrieval Rover to find and gather them for possible return to Earth.

2.4. Mars Helicopter

A possible addition the M2020 mission is a Mars Helicopter flight experiment [8]. As small aerial vehicles have shown their utility for terrestrial applications, the extension to planetary exploration is logical. A helicopter on Mars could provide mapping data and rough terrain access that is complementary to current rover platforms. The Mars Helicopter flight experiment now under development for M2020 is intended to demonstrate the feasibility of aerial mobility in the thin Martian atmosphere. This system is designed to have a mass of ~1.8kg and a rotor diameter of ~1.2m. To date, an experimental model has demonstrated short-duration controlled flight in a chamber pumped down to Mars ambient atmospheric pressure. Compensation for lower Mars gravity was also provided via a suspension system. Figure 2 shows this test in progress. Currently, a flight version of this system is under development. If all goes well, and final approval is granted by NASA, the flight model would be included in the M2020 mission. During the mission, the helicopter would be deployed by the rover, but would not attempt flight until the rover has moved away to a safe distance.

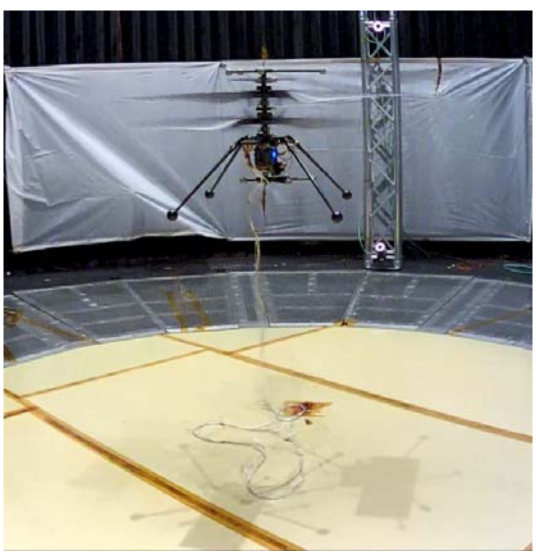

Figure 2: Laboratory chamber tests of the Mars Helicopter test vehicle. Controlled flight was demonstrated in Mars-like atmosphere, with gravity compensation provided by a suspension system.

3 FUTURE MISISON CONCEPTS RESEARCH

In addition to these ongoing flight projects, JPL Robotics has led the development of some key technologies for possible use on future flight projects. For Mars we have been investigating technology for the possible return of samples from Mars, including conceptual systems to fetch the M2020 samples from the surface and place them in a cache that would be launched into orbit from the surface, as well as conceptual orbital technology for capturing the cache and manipulating it for placement in a return vehicle. For Mars or the Moon, we have been developing tethered steep terrain access for slopes, craters, or skylights. For asteroid exploration, we have been developing technology to enable grasping rocky surfaces with micro-spine grippers for stabilization and sampling, and we have developed small CubeSat hopper prototypes for surface exploration. For comets, we have developed a "bi-blade" sampling system that enables the extraction of a wedge of surface material for analysis and possible return. For Venus, we have contributed to the development of conceptual surface sampling systems that can drill in the rock at very high pressure and temperature, and transport rock dust to instruments protected inside the lander. Additionally, we are exploring a suite of other technologies for various venues around the solar system, including compact "pop-up" systems for planetary surface missions, and aerial concepts for exploration of Venus or Titan. The following sections will highlight some of these accomplishments.

3.1 Surface Mobility

A dominant theme in JPL Robotics research is planetary surface mobility. To date, much effort has concentrated on a canonical problem of undulating smooth regolith populated with a relatively sparse set of rock obstacles. This is typical of large sections of the surface of Mars and the Moon. But these planetary bodies also have very geologically interesting areas where steep and rough terrain require other mobility solutions. Examples include craters, canyons, cliffs, caves, lava tubes, sky lights, etc. More importantly, there are science objectives in the solar system that have even more challenging terrain. Examples include that drastic relief and low gravity of comets and asteroids, the fractured and icy surface of Europa, the lakes of Titan, or the snowy surface of Enceladus. All of these present unique challenges for access. Two attributes that exist in many of these venues is steep terrain or low gravity.

Steep Terrain Access: In addition to revealing local geological attributes, steep terrain can also serve as a barrier that must be crossed to achieve other mission goals. JPL robotics has been developing two primary mechanisms to solve this problem: tethered systems to descend, or climbing systems to ascend.

JPL's Axel robot, in Figure 3a, is an example of a tethered system [9]. Designed as a simple two-wheeled rover with tail-dragging stabilizer, it can deploy a tether as it moves across level terrain to steep terrain, down a cliff face, and can even descend vertically suspended only by the tether. Demonstration of this concept has been shown on terrestrial analog terrains, and recent research has concentrated on tether design and management, as well as autonomy for path selection and goal access.

JPL's Lemur robot, in Figure 3b, is an example of a climbing system [10]. The current version of Lemur uses a novel spiny griping system on each limb to grasp rough surfaces such as a rock face. Through repetitive grasp-move-release cycles, it has been demonstrated to climb up a natural rock surface. The design also allows for the optional emplacement of pitons, using each foothold as an opportunity to drill into the rock from center of the foot.

Figures 3a & 3b: The Axel rover (left) going down steep terrain on a tether; and the Lemur robot (right) using spiny grippers to climb a rock face.

Both Axel and Lemur have an aspect of their design that makes them similar to low gravity systems. For Axel, when suspended over steep terrain, the normal force of gravity is small. For Lemur, the design could be applicable for low gravity bodies if solid rock is not covered in loose material. Alternatively, JPL Robotics has explored other designs for low gravity.

Low Gravity Target Access: For mobility in low gravity, such as on a comet or asteroid, hopping is an attractive solution. One mechanism for hopping has been developed by the Japanese space organization [11] – reaction wheel braking to exert an impulse on the terrain and cause the small spacecraft to roll or ballistically jump. JPL has worked with Stanford University to develop a three-axis version of this concept called Hedgehog [12]. Tests completed in the laboratory, simulation, and microgravity have shown its efficacy. Continuing issues for research are an improved system design with integrated instruments, and planning for hopping given the irregular and partially known gravity fields.

An extreme form of hopping is the concept of "touch and go," wherein the spacecraft descends to the surface until establishing contact, and then immediately uses propulsion to move away. This propulsive access is limited by the fuel needed to accomplish it, but can be repeated, and does allow for direct access to desired target locations. This technique has been central JPL's comet sampling concept, shown in Figure 4, which uses a "bi-blade" sampling tool to capture a wedge of material from the surface during the brief interaction with the surface [13].

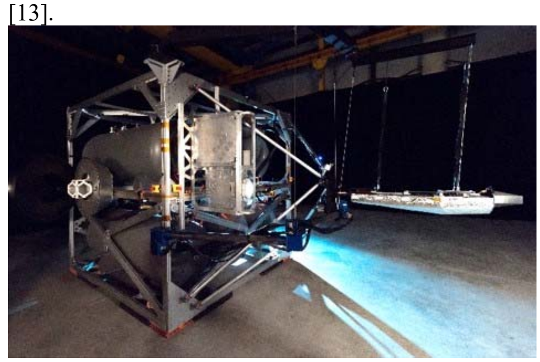

Figure 4: The full-scale comet sampling testbed with three axis mobility via air bearings and propulsion. On the right is shown the bi-blade sampling tool after sample capture from a vertical surface emulating the comet (not shown).

3.2 Orbital Applications

The hopping mobility concepts described above have similarity to orbital applications, due to the ballistic trajectories involved. But two other areas of research for JPL robotics do not involve surface interactions at all. These are described below.

Orbital Sample Preparation for Potential Mars Sample Return: In preparation for possible future return of samples from Mars, JPL Robotics has been investigating ways to automate the gathering of sample tubes on the surface (which would then to be launched into Mars orbit), as well as capture and transfer of the Orbital Sample (OS) container to an Earth return vehicle. Locating and rendezvous with the OS has not be in the scope of this work. Instead, it has concentrated on capture, orientation, and transfer mechanism design [14].

Orbital Construction: To address the needs for improved observation platforms in Earth orbit, JPL robotics has been investigating two approaches. First, we have investigated system design and techniques for orbital assembly of large aperture telescopes from modular components [15]. For instance, we have demonstrated in a laboratory testbed, with a wheeled robot with two arms (Robosimian) [16], the ability to autonomously assemble seven hexagonal truss elements into a circular panel three meters wide. Figure 5 shows this assembly in progress. Due to the repetitive nature of this process, additional rings could be added by this technique.

Figure 5: Autonomous assembly of a hexagonal truss structure representing mirror segments for a large, modular, orbital telescope.

Second, we have been investigating the design elements of a Persistent Robotic Observation Platform for Earth Science [17]. A key feature of this design is the ability to host multiple modular payloads, that can be replaced over time. To handle the payloads and provide services to them (e.g. power and communications), this "Science Station" would have large solar panels and spacecraft bus, and onboard manipulators to receive, move, and emplace payloads.

3.3 Aerial Mobility

Beyond the Mars Helicopter flight test currently under development and described earlier in this paper, JPL Robotics is investigating other aerial mobility concepts for planetary exploration. First, anticipating the success of a first Mars Helicopter, we are exploring future mission ideas that could use aerial mobility for a variety of science and engineering purposes. But issues of scaling, sensing, power, operations, and user training are all important facets of a comprehensive approach to introducing a new mobility platform. Similar challenges existed when we transitioned from static landers to rovers.

Second, we are looking at advanced concepts that might be deployed in the few venues where there is atmosphere to support them. This includes helicopters and balloons for Titan, mobile aerostats for Mars, and balloons for Venus [18, 19, 20].

3.4 Robot Teams

Often when developing a concept for investigation of a specific planetary body, numerous constraints result in the selection of a monolithic system design. But if mass and volume issues can be addressed through miniaturization, then new system architectures are possible. This has been the design impetus behind the Pop-Up Flat-Folding Explorer Robotics (PUFFER) series of rover designs [21], show in Figure 6. Such small systems can be deployed as a team to provide redundancy and also spatially distributed measurements not possible with a single agent. But they also have unique challenges of distributed computation, control, and communication that are currently being addressed by ongoing research.

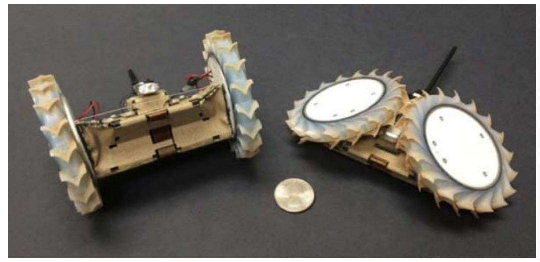

Figure 6: Two PUFFER robots in different configurations. The small size and collapsible design allows for multiple units to be deployed.

3.5 Simulation and Visualization

In addition to hardware and software systems that have been broadly discussed in this paper, JPL robotics also develops modeling, simulation, and visualization for a variety of applications. One body of work is based on the Spatial Operator Algebra formulation [22], implemented in the Dynamics and Real-Time Simulation (DARTS) software system [23]. This system is used for everything from robotics research, to medical research in protein folding, to flight project for Mars, Europa, and the International Space Station.

Additionally, a team of engineers develops visualization software that is used for data interpretation in research and flight, as well as public outreach. Examples have included, MSL/M2020 Entry, Descent, and Landing telemetry visualization, as well as phone and tablet apps for understanding the 2017 total solar eclipse, as shown in Figure 7 [24].

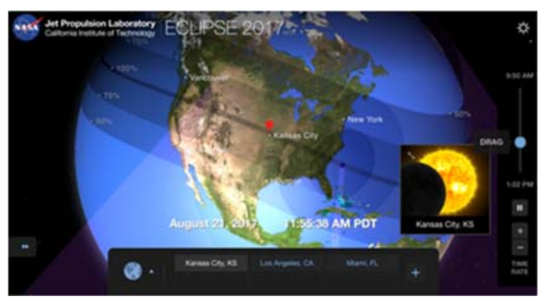

Figure 7: A screenshot of the JPL outreach application for the 2017 total solar eclipse.

4 TERRESTRIAL APPLICATIONS RESEARCH

In addition to the above technologies focused directly on space exploration, JPL robotics is also developing new robotics capabilities for terrestrial applications which can be adapted for future space applications. These systems require a greater degree of autonomy and pave the way for more autonomous system development for space. Some examples of ongoing research work include:

software and algorithms to enable a group of boats to act as a team with a united mission but distributed actions, limbed systems that can traverse very rough terrain and also dexterously manipulate their environment, underwater systems that can create and modify plans for exploration and mapping, and aerial systems that can monitor crops and remain independent for extended durations. A few of these efforts are highlighted below.

4.1 Maritime Systems

A major area of JPL Robotics research for non-NASA applications in in the domain of maritime systems. This work roughly falls in three categories: perception, single boat control, and multi-boat coordination.

Perception: The primary emphasis of this work is to use several techniques to provide long range monocular and stereo image analysis, looking for boats and shore features of interest. Recent efforts enable the fusion of data from a panoramic images, or stereo images horizontally separated across a single boat, or separated across two different craft, as well as vertically separated imagery from a mast [25, 26].

Single Boat Control: This research attempts to capture the capabilities of a human operator to recognize the intent of other boats, and follow the rules of the sea (COLREGS) to safely avoid them [27]. This includes scenarios where other boats are partners, neutral parties, or adversaries. Boats may also have unique configurations, such as towing other craft. Additionally, merging of human and machine planning into one objective is under investigation.

Multi Boat Control: The objective of this research is to develop techniques to control a group of boats in an intelligent fashion to achieve a goal. One major objective is the protection of a larger important asset, such as a mother ship. Perception and single boat control techniques are leveraged in this work [28].

4.2 Land Systems

Our land vehicle research is divided in two categories: control of traditional human vehicles that are being automated, and creation of a new class of small vehicles that have unconventional capabilities.

Multi Vehicle Control: Mirroring the maritime work above, we are also developing techniques for coordination of ground vehicles. However, this work concentrates more on scenarios such as convoy formation control for resupply and road reconnaissance. Unlike the open water work with boats, the ground vehicle solutions are intended to be restricted to passable roads, changing the solution space available [29, 30].

Small Vehicles for Climbing: To climb vertical walls, we are investigating a number of techniques to grasp or stick to the surface. These include, synthetic gecko skins, electrostatic pads, and arrays of hooks [31, 32, 33]. These methods are used alone or in conjunction to provide multi-surface capability. Typically, we integrate them into the equivalent of wheels, to allow driving up the target surface. Figure 8 shows two models of these vehicle.

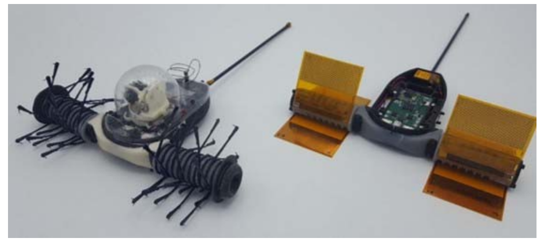

Figure 8: Two research vehicles that have the ability to climb vertical surfaces. The left vehicle is designed for rough surfaces, while the right is better at smooth. For scale, the vehicle axles are 15-20cm long.

4.3 Aerial Systems

Control of Fast Drones: We have been pushing the envelope on how fast a high-speed drone can be flown while using visual features to maintain its pre-selected flight path [34]. This work grew out of the Google Tango project, and is called Tango on Racing Quadrotors (TORQ). The results showed autonomous trajectory following is comparable to human piloting while racing in a cluttered warehouse [35].

5 CONCLUSION

This paper has traced the breadth of JPL Robotics efforts from flight project development, to basic research (NASA and non-NASA) which will provide technology for future mission infusion. In addition to the overview of these activities, some historical context has been provided, as well as examples of the technology infusion process that has enabled these achievements.

Acknowledgement

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The information presented about future space mission concepts is pre-decisional and is provided for planning and discussion purposes only.

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