

AUTONOMY TECHNOLOGY AT JPL

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ABSTRACT

This paper and exhibit describes the on-going research activities, plans and products of the Autonomy Technology program at NASA Jet Propulsion Laboratory. This program includes work in the many areas. In this paper, we briefly describe the areas of Mission Planning and Execution, Distributed Autonomous Systems, Science Data Understanding, and Autonomous Guidance and Control.

As mankind extends its presence further through the Cosmos, into often unpredictable and unexplored environments, a new breed of autonomous spacecraft will be required. Due to the light-time communication delay inherent in deep-space travel, direct human control will be infeasible. These future explorers will need to be highly capable of responding intelligently to unexpected events, recognizing and avoiding hazards, seeking out science opportunities and recovering robustly from faults.

Autonomy will be an enabling technology for visionary missions such as submarine exploration of the oceans believed to lie beneath the icy crust of Europa, colonies of intelligent collaborating robots on Mars, and sustained-presence missions that require spacecraft to survive while meeting science objectives over long periods with minimal human intervention. In addition, greater spacecraft autonomy is needed in order to reduce mission operations costs, and enable cost-effective control of multiple-spacecraft missions.

As part of NASA's Intelligent Systems Program, managed by NASA Ames Research Center, JPL is conducting focused research in several areas, including integrated mission planning and execution, team execution and fault protection, and on-board science. These technologies address pacing challenges and provide enabling capabilities for future NASA missions. These efforts will enable a space flight mission to build the automated reasoning components necessary for a major experiment and demonstration of flexible sequence generation and execution with opportunistic science exploration in multi-rover and/or spacecraft constellation scenarios.

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.

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Keywords Autonomy, autonomous rover, distributed systems, planning, control, commanding, architecture, hazard detection.

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1. INTRODUCTION

As mankind extends its presence further through the Cosmos, into often unpredictable and unexplored environments, a new breed of autonomous spacecraft will be required. Due to the light-time communication delay inherent in deep-space travel, direct human control will be infeasible. These future explorers will need to be highly capable of responding intelligently to unexpected events, recognizing and avoiding hazards, seeking out science opportunities and recovering robustly from faults.

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experiment and demonstration of flexible sequence generation and execution with opportunistic science exploration in multi-rover and/or spacecraft constellation scenarios.

2. MISSION PLANNING AND EXECUTION

Intelligent planning and execution technologies are being developed that enable spacecraft to be commanded with high-level goals rather than detailed sequences. The spacecraft possesses, in on-board software, the knowledge and reasoning procedures for determining the actions needed to achieve those goals while preserving spacecraft health. The spacecraft continually monitors itself and its environment, and changes its course of action as needed to achieve its goals. These capabilities reduce operations costs and enable robust operations in dynamic and uncertain environments.

Traditional autonomy architectures make a strong separation between the planning and execution functions, and they are implemented as distinct component technologies. This separation complicates knowledge engineering and limits the responsiveness and robustness of the system. Our research effort is developing and implementing a framework that enables tighter sharing of information and capabilities between the planning and execution components of autonomous systems in order to address these issues. Specifically, the framework includes mechanisms for the execution component to utilize the planning component's constraints and decisions in making its decisions; for the planning component to specify constraints procedurally utilize the execution system's procedural functionality. The exploration of trade-offs between execution and planning is an important consideration of this work in progress.

3. DISTRIBUTED AUTONOMOUS SYSTEMS

Future NASA missions will involve multiple spacecraft or rovers that must interact with each other to achieve their mission goals. Commanding a constellation by issuing individual sequences of timed commands to each spacecraft would not only be cumbersome and expensive, but it would be nearly impossible to command coordinated activities--imagine trying to play catch by reading a script that tells you exactly when to put your hand up and close your fingers.

Commanding multiple spacecraft is qualitatively different than commanding single spacecraft. One must specify not only what individual spacecraft should do, but also how the spacecraft should coordinate their activities. Spacecraft teams must also be able to detect and respond to team faults—that is, failures in coordinated activities that cannot be detected or responded to by individual spacecraft, but only by multiple spacecraft working in concert. Commanding multiple spacecraft is also quantitatively different—operations procedures that work well for a single spacecraft may not scale up to multiple spacecraft.

New autonomy technologies are needed that can operate a constellation as a coordinated entity by issuing collective mission goals instead of individual command sequences. Developments are currently underway in team planning and execution. These technologies extend single-spacecraft planning and execution technologies to deal with the myriad coordination issues faced by spacecraft constellations and rover fleets.

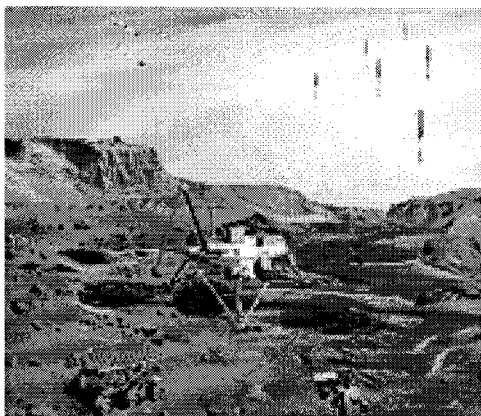


Figure 1: Multi-vehicle exploration

JPL is developing technologies for defining and executing a course of action for coordinated team of agents (rovers/spacecraft), and for identifying and responding effectively to ‘team-faults’—that is, faults that cannot be detected or responded to by a single team member, but only by multiple team members. The scope of our work includes developing a language for specifying “team plans”, and developing a “team executive” that runs on each spacecraft in a population to carry out team plans and to detect and respond to “team faults.” We are evaluating the above research products in the context of spacecraft and/or multi-rover simulation testbeds.

4. AUTONOMOUS GUIDANCE AND CONTROL

Exploration of solar system surfaces requires robotic systems that can navigate, land, and avoid hazards. Due to

the small size, irregular shape and variable surface properties of small bodies, accurate position estimation and hazard avoidance are needed for safe and precise small body landing and sample return. The communication delay induced by the large distances between the earth and targeted small bodies adds additional complications. Our conclusion is that landing on such surfaces requires on-board intelligence that can quickly assess the situation and react quickly to changing events. Current navigation technology does not provide the precision necessary to accurately land on small bodies, so other positioning techniques must be investigated.

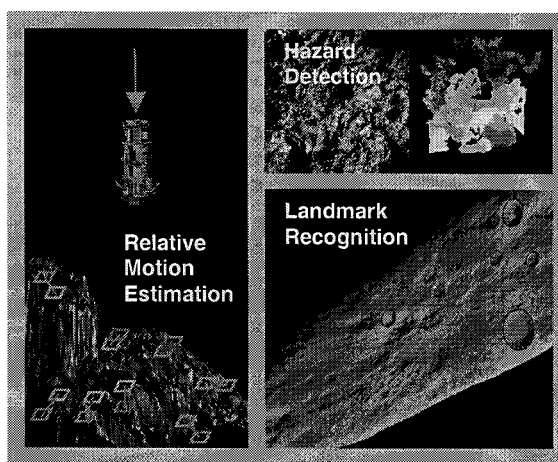


Figure 2: Visual position estimation

Optical sensors combined with autonomous machine vision algorithms offer a solution to the precise positioning problem; images can be automatically analyzed to determine the position of a spacecraft with respect to a proximal body. Machine vision technologies are being developed that can recognize landmarks for navigation, estimate spacecraft motion by analyzing the relative motion of surface features, and identify safe landing sites. Recent work has been focused on developing a system for autonomous absolute position estimation around asteroids using crater landmarks. This system is being evaluated using real imagery collected of the asteroid Eros by the NEAR spacecraft. JPL is also developing a system for autonomous absolute position estimation over comet-like terrain by matching shape-based invariants. This system is being evaluated using real imagery collected by a helicopter testbed flying over natural terrain.

These technologies will be combined with guidance and navigation control algorithms to provide an integrated capability for precise navigation, landing, and hazard avoidance.

5. SCIENCE DATA UNDERSTANDING

Future missions will require systems that automatically identify scientific events in instrument data. Technologies currently under development in this area include trainable sunspot recognizers, detectors for craters and volcanoes, and systems that find natural satellites of asteroids. As part of ground-based systems, these technologies enable scientists to automatically mine vast spacecraft data volumes for the information they need. Combined with onboard planning and execution technologies they enable the scientists to prioritize and summarize data onboard, to scan high-rate data streams for short-lived or hard-to-find events, and to detect and exploit fast-breaking science opportunities such as eruptions or solar flares that would otherwise be lost.

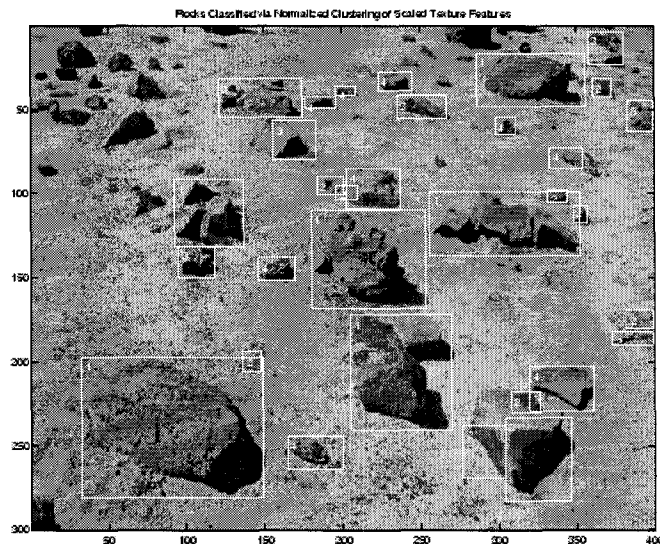


Figure 3: Automated science classification

JPL is researching on-board science for multi-rover missions. Our research effort lays the essential groundwork for a project to build the onboard science processing portion of a major experiment and demonstration of intelligent systems in a Mars multi-rover exploration scenario. Recent efforts have been directed at extending the current library of mathematical models of geological processes, and development of algorithms for collecting and interpreting science data. Our current focus is on identifying the requirements on autonomy architectures needed to support on-board science and mature automated planning technologies for developing and commanding science acquisition plans for single and multiple rovers based on the results of on-board science processing. The ultimate goal is to produce a hypothesis-driven, autonomous rover operation and science understanding system. The research products of this work are being experimentally evaluated on rover and/or computer testbeds.

6. CONCLUSIONS AND FUTURE DIRECTIONS

Advanced Computing and Software Engineering Autonomous systems are highly complex and operate in mission-critical environments. Advances in software engineering and validation are needed to minimize development costs and ensure high reliability. These include research into autonomy architecture design, validation of model-based systems, and unified knowledge-engineering languages. Researchers are also working towards a powerful new kind of computer based on the properties of quantum physics. These quantum computers will be able to solve problems that are intractable for classical computers. Autonomous systems implemented on quantum computers could exhibit wildly faster reaction times and far greater reasoning power. Such computers would also have far ranging commercial applications that could revolutionize the computer industry.

7. ACKNOWLEDGEMENTS

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