Demonstrating Robotic Autonomy in NASA's Intelligent Systems Project

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INTRODUCTION

To accomplish the next generation of challenging missions to the Moon, Mars, and beyond, NASA will develop autonomous systems that can make critical decisions independently of human operators. Autonomy technology will extend the boundary on what can be accomplished in future missions by overcoming limitations due to communications delays, light-speed constraints, mission complexity, and cost. Autonomous systems will enable future space missions by maintaining vehicle health and safety, accomplishing complex science and mission goals, and adapting to changing circumstances or opportunities.

This paper provides an overview of NASA's recent investments in autonomy within the Intelligent Systems (IS) Project. The paper is divided into three parts: first, a brief overview of the IS project; second, a description of the Automated Reasoning element of the IS project, including a discussion of the autonomy milestone, which forms the basis for the contributions made by three specific IS projects. The third part of the paper contains a detailed summary of the three projects.

OVERVIEW OF NASA'S INTELLIGENT SYSTEMS PROJECT

The goal of NASA's Intelligent Systems (IS) Project is to develop smarter, more adaptive systems and tools that work collaboratively with humans in a goal-directed manner to achieve NASA mission goals. These systems are required to meet NASA's near-term mission needs for Earth observation, deep space exploration, and human exploration of space. At the same time, IS has focused on longer-term strategic technology objectives which are achievable over a 15-20 year time span. The IS project has involved a close partnership between NASA, academic, and industry researchers.

The IS Project has focused on technologies for **automated reasoning**, **human-centered computing**, and **intelligent data understanding**. The focus of this paper is on the first class of technologies, discussed in more detail below. Broadly defined, human-centered computing technologies are those that contribute to optimizing the combined performance of human experts and the supporting information system. Intelligent data understanding technologies are software systems that contribute to understanding, and discovering new information from, large databases. (For more information on the IS Project, please consult the IS website [1].)

Automated Reasoning includes technology that provides the key enabler to the development of **autonomous systems,** complex integrated hardware/software systems that can make decisions with little or no human intervention. Autonomy describes a set of capabilities that allow a spacecraft or other complex system to react to uncertainties within the environment in a robust fashion while achieving a set of high-level goals or objectives. Autonomous systems include robotic explorers with autonomous guidance and control, on-board science interpretation, and intelligent vehicle health maintenance.

The goal of the Automated Reasoning program element of the IS Project has been to develop core technologies that facilitate the development of autonomous systems and to develop the infrastructure required to rapidly develop, test, verify and maintain these systems. The culmination of NASA's investment in autonomy in the IS project is an on-going series of demonstrations of analogue rover science missions demonstrating key autonomy technologies enabling goal-directed systems for science exploration missions. These projects each contribute to the accomplishment of the IS program milestone in autonomy, defined in the IS Project Plan [1] as:

Conclude a successful analogue science mission (terrestrial rover or simulated spacecraft) demonstrating key autonomy technologies enabling goal-directed systems for science exploration missions. Demonstrate technologies enabling contact instrument placement and vehicle positioning in one command cycle. Demonstrate on-board autonomous instrument targeting capability based on serendipitous science opportunity. Key technologies include: planning/scheduling, science data priority assignment, system executives, and diagnostic systems.

The remainder of this paper describes a technical overview of three projects that have contributed directly to meeting the autonomy milestone.

IS MILESTONE PROJECTS

Although there is a degree of overlap in the capabilities demonstrated by each of the three milestone projects summarized in this section, there are also technologies and capabilities that uniquely distinguish each project from the others. The **Autonomous Instrument Placement** project focuses on the set of capabilities that will enable a rover to autonomously navigate to a designated geologic target and place a robotic arm on the target for the purpose of collecting samples or conducting close imaging. The **Continuous Planning and Execution** project's focus is on a set of capabilities supporting long-range autonomous traverse and exploration of multiple geologic targets. Finally, the **Hybrid Discrete/Continuous System for Health Management** project focuses on capabilities that will ensure that a complex space system is able to detect, diagnose, and recover from system failures. The remainder of this section will describe each project in detail.

Autonomous Instrument Placement (PI: Liam Pedersen, NASA Ames Research Center)

This research was motivated by the need of the planetary science community to acquire close up and contact measurements from a variety of targets on the surface of a planetary body. State-of-the-art planetary rovers, such as the MER rovers (Spirit and Opportunity) currently on Mars require 3 days and a standing army of operators on Earth to accomplish the task of driving up to a target and safely placing an instrument against it. With limited mission lifetimes and operations costs exceeding $1 million per day, decreasing this time and the number of operators has a significant scientific and cost-reduction pay-offs. This project is building the capability for a rover to visit and examine multiple targets, scientific or otherwise, over 10's of meters in an un-prepared environment in one command cycle and without supervision from mission control. Using K9, a six wheeled planetary rover prototype, we have successfully demonstrated this in field locations, with operators at NASA Ames communicating to it via satellite. This project is building and integrating the diverse capabilities for an exploration rover to rapidly and reliably do close up inspections and in situ measurements of objects in an unstructured and unpredictable environment or worksite, with out continuous operator supervision. This efficient goal level commanding capability represents an order of magnitude improvement in MER inspection capabilities whilst requiring less operator support.

Achieving this level of performance has required advances across a broad technological front, primarily in the areas of:

- *Target tracking and instrument placement* technologies [7] to enable a rover to autonomously visit and examine many samples distributed over a 10m radius area with centimeter precision. Because of wheel slippage and cumulative inertial guidance position errors, a rover cannot keep accurate track of goal locations around it using deduced reckoning alone as it moves towards them. Our solution has been the development of stereo-vision techniques using keypoints and 3D target templates to continuously track targets. Once at the goal location, our auto-place algorithm permits the rover to distinguish rocks and other potential targets from the ground (regardless of slope or surface texture) and find instrument placements consistent with any limitations imposed by the tool and the target geometry.

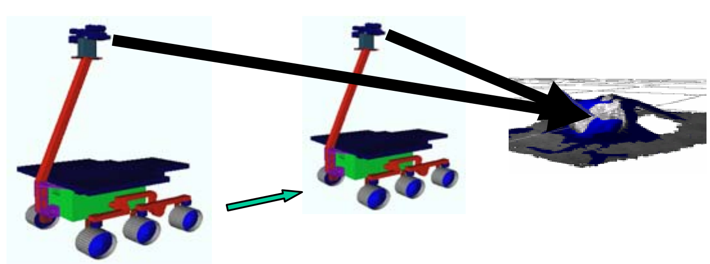

Figure 1. Navigation and Tracking

- *Robust and flexible planning and execution* [8] for the rover to accommodate the great uncertainty associated with navigating to and deploying instruments on multiple samples, whilst adhering to power and resource constraints characteristic of a planetary rover. Standard mission practice is to generate daily activity plans offboard, permitting operators to modify and verify them prior to uplink. Whilst suitable for predictable systems, such as satellites in orbit, this approach copes poorly with uncertainty. We have developed a ground based contingency planner that generates a main line rover activity sequence with flexible time constraints and contingent activity sequences to accommodate off-nominal behavior. These include diverting to closer targets if resource use is excessive and recovering from target tracking failures. The rover CRL Executive executes these plans whilst monitoring resources and faults, and doing minor plan reevaluations as required. This approach combines the benefits of the traditional approach with some of the flexibility but not the risk of an onboard planner.

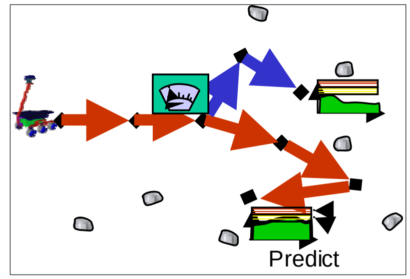

Figure 2: Contingency Planning

- *Ground systems* [9] for users to rapidly identify, prioritize and specify many potential targets, evaluate the plan of action, and understand the data returned from the multiple samples the rover actually visited (which may differ from the highest priority set requested). Our operator interface uses the Viz software to immerse users in a photorealistic VR, 3D display of the environment around the rover. Within this, the users rapidly specify daily mission goals and evaluate returned data.

A summary of the technology goals of the project occurs in Table 1.

Table 1 : Technology Goals for Instrument Placement Project

Technology	Supporting Goals
1. Fully autonomous navigation to targets and instrument placement	a. Autonomously track and navigate to science targets within local area, chosen by users b. Autonomously place science instruments against rock targets, ensuring instrument and rover safety.
2. Contingent planning and robust execution for rover to adapt to increased uncertainty associated with autonomous navigation and instrument placement, whilst adhering to stringent resource (power and time) constraints.	a. Flexibly adds/remove science goals in response to changes in resource availability and usage (power, time). b. Obtain follow-up measurements to exploit new science opportunities discovered by on-board data analysis. c. Adapt science goals in response to basic faults (loss of target, inability to place instrument)
3. Effective ground data systems for users to interact with rover that operates for long durations under considerable uncertainty	a. Interface for users to express science goals b. Interface for users to plan/evaluate daily rover activities c. Enhance users situational awareness after complex activity plans with many uncertainties and variations d. Understand science user needs for interacting with highly autonomous systems

In October 2003 the first successful integrated end-to-end demonstration of the technologies was conducted at the Granite Rock Aromas quarry near Watsonville, CA. That demonstration consisted of the following scenario:

- Operators at NASA Ames Research Center designated 2 targets in Viz.
- The planner, with humans in the loop to choose branch points, was used to generate a plan to visit on of the 2 targets, branching on energy.
- The plan was uplinked via satellite to the field location and executed on K9.
- K9 tracked both targets using mesh registration and placed CHAMP on one of them as dictated by the plan.
- During the traverse, science autonomy routines detected layers on a nearby rock, triggering a floating contingency that directed the rover to acquire hi-resolution follow up images of the target.

A final demonstration of the integrated single cycle instrument placement technologies will be held in the fall of 2004.

Continuous Planning and Execution (PI: Tara Estlin, NASA/Jet Propulsion Lab)

The overall objective of this IS Milestone Project is to perform intelligent decision-making onboard a rover and to provide autonomous capabilities for opportunistic science handling and other dynamic rover-schedule adjustments that help handle the uncertainty of mobile surface operations. These capabilities will help reduce overall mission operations costs by automating certain decisions to be made onboard. They will also enable new science opportunities to be realized that could not be achieved given current mission operations. Collected science data is currently analyzed on Earth and this time-intensive process does not allow for the dynamic adjustment of rover behavior. With current mission operations, a rover may have traveled many meters or kilometers past an interesting object before additional measurements can be scheduled. The JPL project primarily focuses on using continuous planning and execution techniques as part of a rover's onboard software to provide autonomous sequencing functionality. This technology accepts science and engineering goals, creates a rover command sequence (or plan) to achieve the goals, manages resource and state constraints, executes that sequence by interfacing to lower-level rover control software, and dynamically modifies that sequence based on changing goal, state and resource information. The JPL project also highlights related work funded through the Intelligent Systems Program, which is directed at the onboard analysis of collected rover-science data to detect interesting terrain features during rover traverses. These technology elements have been integrated and tested together on numerous rover traverses for varying science targets using several JPL rover platforms.

Planning, scheduling, and executive capabilities for this work are provided by the Continuous Activity Scheduling, Planning and Re-Planning (CASPER) system [3], [4], and the Task Description Language (TDL) executive system [6]. CASPER components include a constraint management system for representing and maintaining domain operability and resource constraints, a set of planning and scheduling search strategies and repair heuristics, and a real-time system that monitors plan execution and modifies the current plan based on activity, goal, data and resource updates. TDL was designed to perform task-level control for a robotic system. It expands abstract tasks into low-level commands, executes the commands and monitors their execution. It also provides support for exception handling and fine-grained synchronization of subtasks.

These systems were integrated into the Coupled Layered Architecture for Robotic Autonomy (CLARAty) [5]. CLARAty is a unified and reusable architecture that simplifies the integration of new technology on robotic platforms. Currently, CLARAty is operational on a number of NASA and university rover and robot platforms. CLARAty allowed the developed technology to be tested with different rover hardware and enabled the coordination of CASPER and TDL with several levels of rover control software, including navigation, path planning, and vision control.

Data analysis capabilities were provided by the Onboard Autonomous Science Investigation System (OASIS) [1]. OASIS contains modules for autonomously locating rocks in images (shown in Figure 5), extracting features (or rock properties) from those images, such as albedo, shape and texture, and analyzing this data to determine if identified rocks fit target or novel signatures, which indicate rocks of significant interest. If highly interesting rocks are discovered, the analysis system can signal the onboard planner to perform new science observations. The planner will then attempt to schedule these new goals given current rover resource and state constraints.

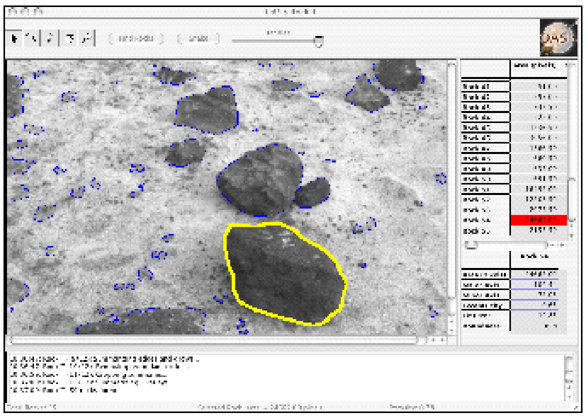

Figure 3: Rock identification from sample image.

Figure 4: Rocky 8 rover (left), FIDO rover (middle), Rocky 7 rover (right)

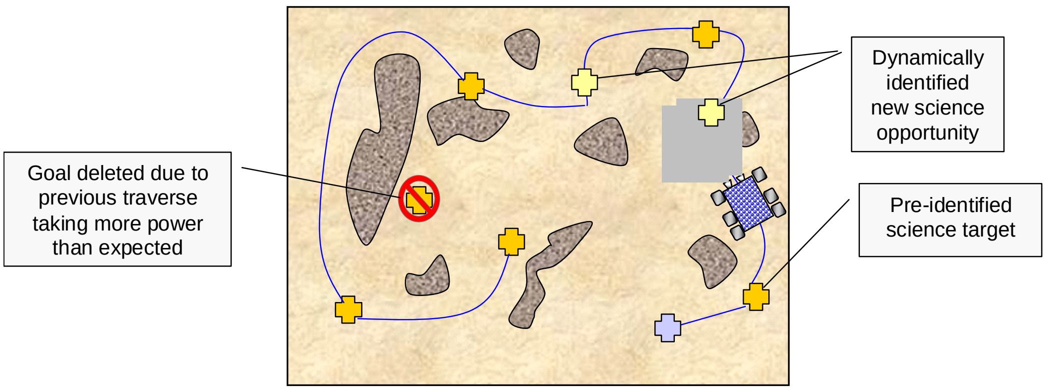

Figure 5: Sample rover scenario run in JPL Mars Yard.

To evaluate the final system, we performed a series of test in the JPL Mars Yard using several rover hardware platforms, including the Rocky 7, Rocky 8 and FIDO rovers (see Figure 4). These tests covered a wide range of scenarios that included the handling of multiple, prioritized science targets, limited time and resources, opportunistic science events, resource usage uncertainty causing under or over-subscriptions of power and memory, large traverse time variations, and unexpected obstacles blocking the rover's path. Recent tests have used the FIDO rover and are focused on realizing new science opportunities that are dynamically identified (based on rock albedo) during the rover's traverse, as well as handling uncertainties in time and power usage, which may cause certain science targets to be added or removed from the current plan. A large focus of these tasks is to evaluate system robustness and flexibility by testing on large variations of science target locations (including both pre-known targets and science targets identified opportunistically through data analysis). Tests typically consist of 20-40 meter runs over a 100 square meter area with many obstacles that can cause deviations in the rover's path. An example scenario is shown in Figure 5, which includes several opportunistic science events and one deletion of a science target due to an earlier traverse taking more power than originally estimated.

Future activities will expand our technology development and testing to handle longer traverses, additional state and resource variations, as well as further opportunities for new science detection (e.g., using rock color or texture). In summary, we have developed a new approach for onboard rover sequence generation, execution, data analysis, and re-planning, which can be used to make intelligent sequencing decisions onboard the rover itself, thereby reducing overall operations costs and enabling new science opportunities to be successfully handled.

Hybrid Discrete/Continuous System for Health Management (PI: Brian Williams, Massachusetts Institute of Technology)

This project develops a hybrid estimation, monitoring, diagnosis and model learning capability for physical devices that exhibit complex discrete and continuous behaviors. For the purposes of estimation, best-first search is used to track the most likely modes, whilst a bank of filters track the continuous system dynamics. Existing health management systems model component behavior with a finite number of discrete modes, representing nominal and off-nominal operation.. In addition, no provision is made for modeling system dynamics. This approach lends itself to situations in which component failure is discrete and catastrophic, such that the models describing different component modes represent very different behaviors.

As a result, this approach is incapable of modeling systems in which the symptoms of component failure are subtle and may develop gradually over time. Recent mission anomalies (e.g., Mars Climate Orbiter, Polar Lander, Spirit) highlight the need for monitoring capabilities that are able to detect subtle symptoms, and simulators that can be quickly tailored to a particular mission.

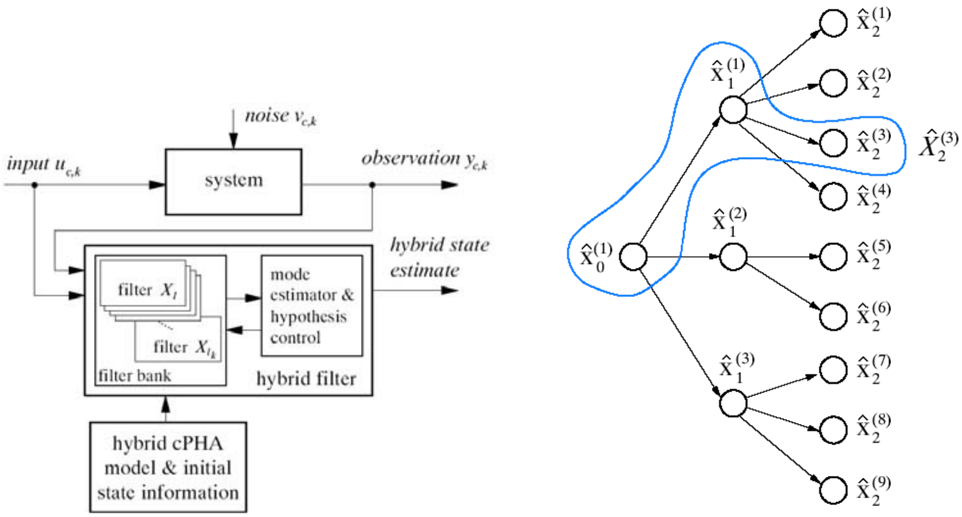

Figure 6. System Architecture and Search

The monitoring and diagnosis software must track the system's behavior along both its *continuous state changes* and its *discrete mode changes* and their system-wide interaction. The plant is represented by a decomposed model in which each component is described by a separate concurrent Probabilistic Hybrid Automaton (CPHA) [12]. This model represents a component's state with both discrete and continuous variables. Discrete variables represent the component's possible modes, classifying each as either a nominal or a fault mode, as well as guarded, probabilistic transitions between these modes. For each mode, the evolution of the continuous variables is described using discrete-time dynamics. In addition, the PHA tracks the discrete and continuous state; the discrete and continuous command inputs; and the continuous output. This decomposed approach allows accurate modeling of complex systems, as component failure can be represented by mode transitions at the component level, resulting in altered dynamics for component only. In addition, modeling the plant with many CPHA rather than a single large automaton greatly reduces the overall complexity of the filtering task.

Our approach is to use search methods to track the evolution of the discrete modes, and Gaussian filtering to track the continuous state. Our current implementation uses a bank of Kalman filters for the estimation and filtering of the continuous variables, but the structure is independent of the filter type. Two possible methods were considered for tracking the discrete mode.

- **K-best Filtering** [11] In this case, estimation of the discrete mode is formulated as a best-first search, in which the *k* leading mode trajectories are maintained. The search tree of mode transitions is expanded component-wise, using A* to search the space of possible successors.
- **Multi-modal Gaussian Particle Filtering** This approach uses particle filtering to track the evolution of the discrete modes. Again, the mode transitions are expanded component-wise and a particle sample is taken at every transition. The scheme is derived from Rao-Blackwellised particle filtering. The key step is to reuse the continuous state estimate in the evaluation of transition probabilities.

Another product of this work is the development of algorithms for automatic decomposition of hybrid models.

The capabilities of the hybrid health management system were demonstrated on simulations of NASA JSC's Advanced Life Support System and of simple robotic limbs [10].

- **Advanced Life Support System** This simulation used modeled the CO_2 and O_2 control subsystem; resulting in over 450,000 different modes by the end of the simulated trial. Both the k-best filtering and the automatic decomposition algorithms were tested. The results demonstrated the systems' ability to robustly diagnose system failures and to detect the presence of astronaut from the measurement data available from gas concentration sensors.

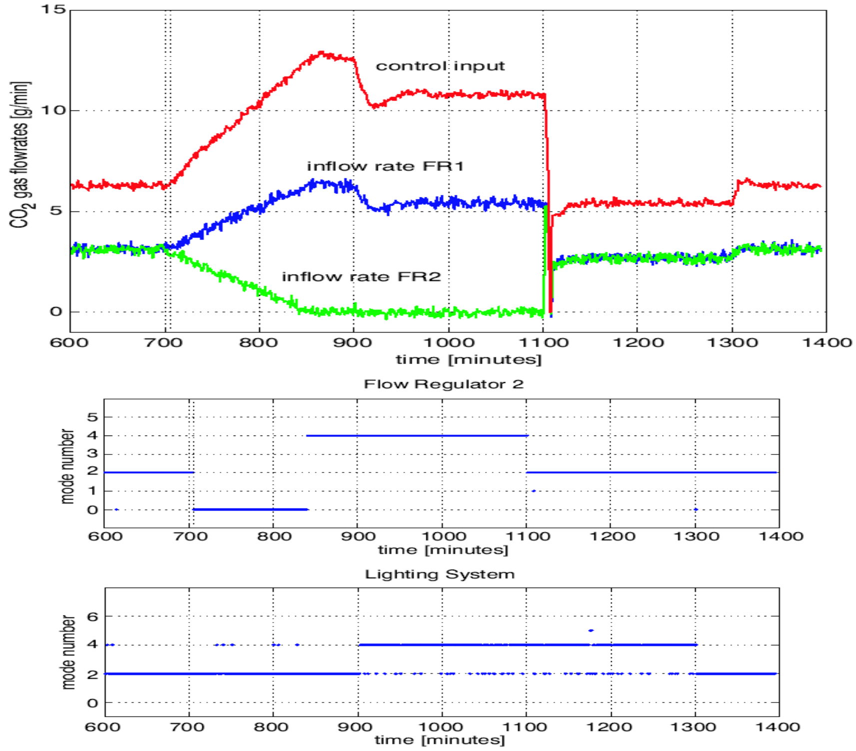

Figure 7. Experiment Results

- **Robotic Limb** The hybrid health management system was used to diagnose actuator failure in a simulated robot leg.

The results of this work are Hybrid Mode Estimation algorithms for Concurrent Probabilistic Hybrid Automata (CPHA). Algorithms for Multi-Modal Particle Filtering and for the automatic decomposition of hybrid models have also been developed. These developments include the following key innovations.

- Dynamics are modeled as concurrent probabilistic hybrid automata (CPHA)
- Monitoring, diagnosis, and state/fault tracking framed as Gaussian particle filtering on HPCA
- Model learning framed as Expectation Maximization for CPHA

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CONCLUSION

This paper has described the results of NASA's five year investment in autonomous system technology as part of the IS project. The result of this investment has been a maturation of automated reasoning software technology through integration into complex hardware and software systems to accomplish complex goals related to surface exploration and spacecraft control. The project's autonomy milestone has been successfully accomplished through a series of demonstrations of these technologies in realistic analog mission settings. Although not the primary topic of this paper, it should be mentioned that some of the technologies discussed here have already been integrated into the MER mission in the form of ground support tools. The future will require the continuous development of strategies for insertion/infusion of these technologies into future missions to Mars and beyond.

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