MISUS: Multi-rover Integrated Science Understanding System

JPL Task Team:

Tara Estlin (PI), Rebecca Castano, Ashley Davies,
Forest Fisher, and Daniel Gaines

Wesleyan University Collaboration:

Martha Gilmore

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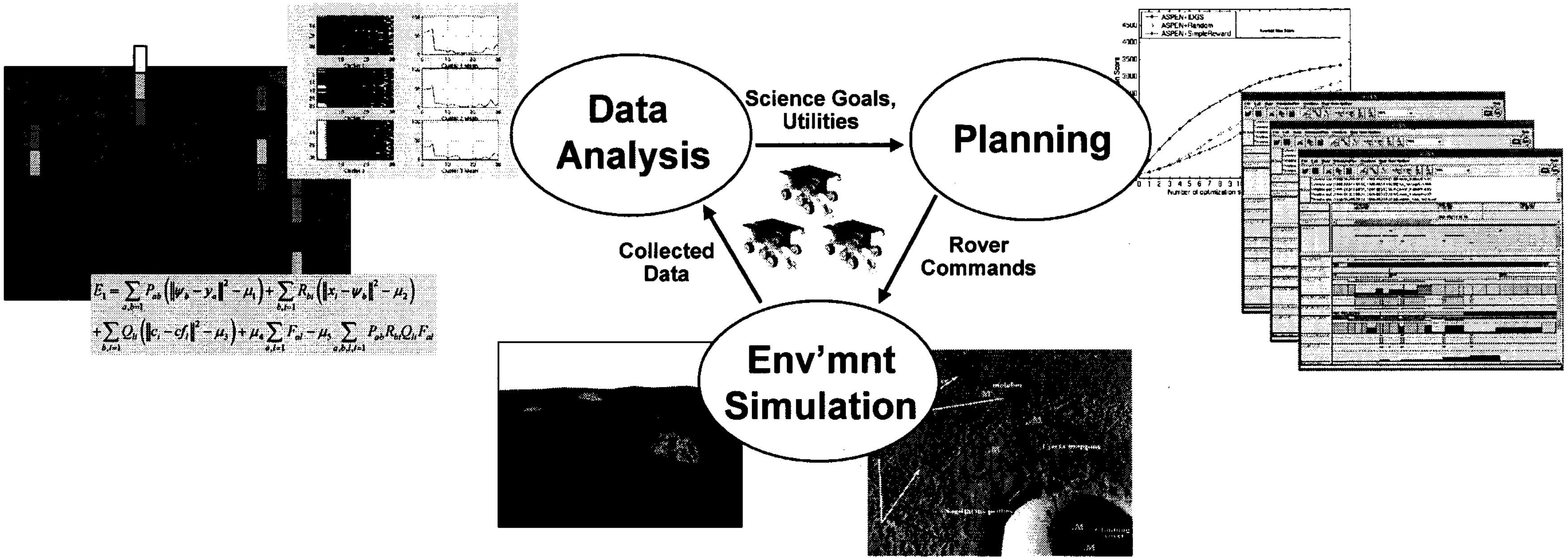
MISUS Approach

- Framework for coordinating multiple rovers in performing autonomous science operations
  - Provides an onboard science capability for collecting new data
  - Enables rover team to autonomously investigate new environment
- System integrates techniques from machine learning and planning/scheduling
  - Data analysis
  - Generates new science goals
  - Produces valid plans to achieve goals
  - Monitors plan execution and performs re-planning
- Also integrated with a simulation environment that models different planetary terrains
- ***Key feature:*** closes the loop between sensor data collection, science goal selection, and activity planning and scheduling

System Overview



1. ***Data Analysis:***
   - Machine-learning clustering system
   - Analyzes input data and constructs summary model
   - Generates and prioritizes new science targets
2. ***Planning:***
   - Distributed, continuous planning system
   - Produces rover operation plans to achieve input science goals
   - Monitors plan execution and re-plans when necessary
3. ***Environment Simulation:***
   - Models geological environments and multiple rover science activites within them

Key Task Objectives

- Interdependent science goals
  - Science goals/objectives are typically considered independently
  - Goals are often related – science utility of a goal can increase/decrease if related goals are achieved
  - Investigating methods for reasoning about these interdependent relations to both generate better goals and higher quality plans
- Applying onboard data-analysis and planning techniques to planetary field geology
  - Analysis techniques uses terrain model of mineralogical deposits to help identify areas and rocks of interest
  - Overall goal is to identify rock composition and deposit classification
- Enabling a distributed rover team to efficiently perform terrain investigation
  - Goal assignments may dynamically change based on rover and environment status
  - Goal information is shared to improve quality of overall collection

Schedule and Milestones

- FY01
  - Developed distributed planning system for producing multi-rover operation plans and monitoring execution
  - Developed data analysis algorithm for evaluating geological relationship among data
- FY02
  - Developed planning optimization approach for interdependent science goals
  - Developed prioritization algorithm that uses learned data model to generate new set of observation goals
  - Extended environment simulator to incorporate more realistic terrain distribution
- FY03
  - Fully integrated new planning and analysis approaches
  - Improved system robustness and tested running continuously over multi-day scenarios
  - Extended infrastructure to support easier demonstration and evaluation
- FY04
  - Perform full system evaluation
  - Perform simulation and hardware demonstrations

Recent Accomplishments

- Extended planning optimization approach for interdependent goals to operate in distributed environment
  - Goal status information is shared between rovers
  - All agents can use interdependency information and current goal status to guide new goal additions
  - System attempts to continually assign unachieved goals to improve overall quality of collected data
- Increased distributed planning capability for handling larger quantities of science goals and more uncertainty
  - Improved scheduling heuristics to maximize rover resources
  - Adapted improved distributed-coordination capability to allow better consistency and communication between plans

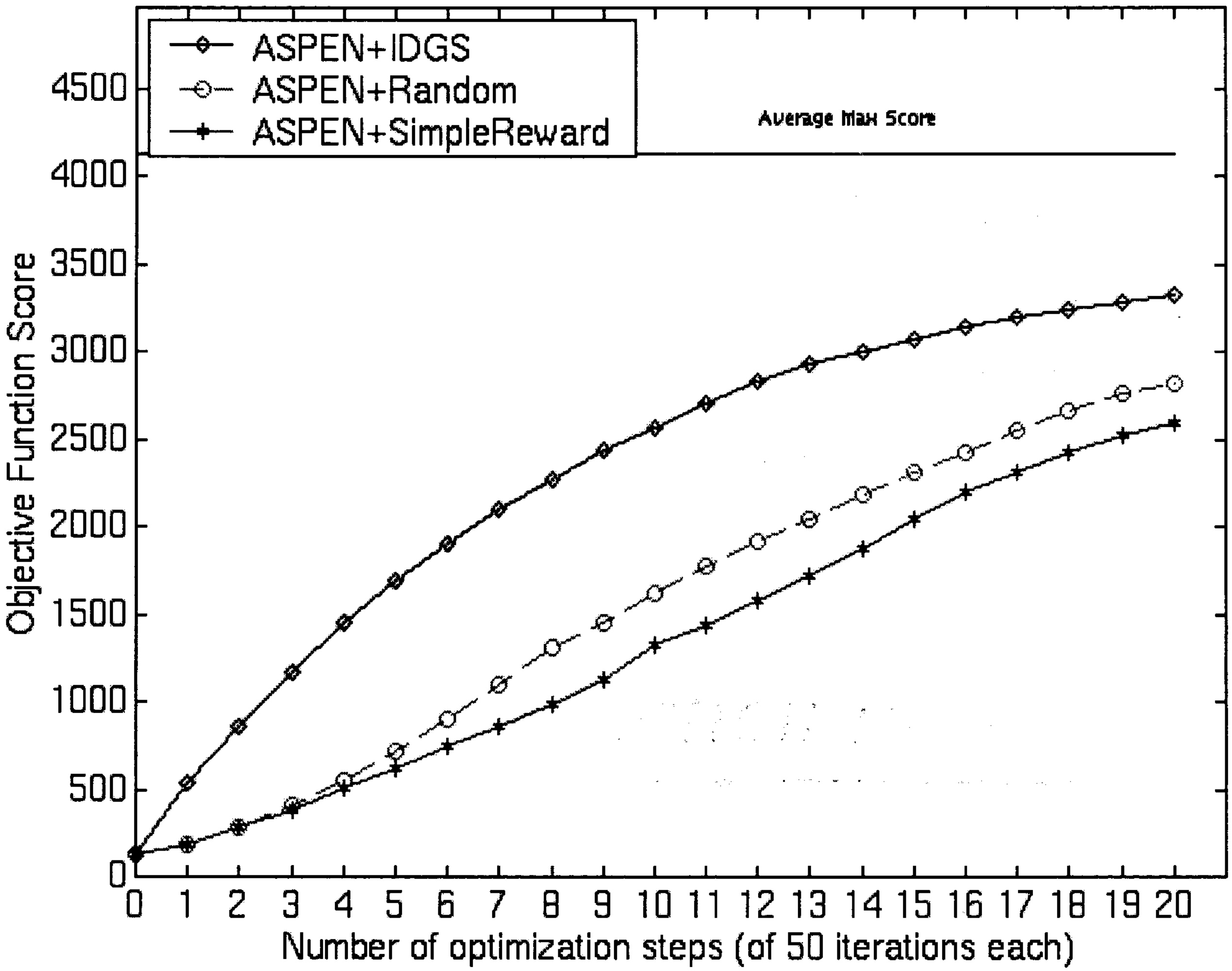
Recent Accomplishments, cont.

- Completed integration of all new system components
  - Closed-loop between new versions of planner, data analysis, and environment simulator.
  - Tested full closed-loop system running autonomously for several Martian days
- Developed several key software pieces to enable easier testing and demonstration
  - Time warping capability for distributed plan execution and monitoring
  - Implemented two other applicable data-analysis algorithms to provide comparison with MISUS approach
  - Created new display tool that allows easy visualization of mineralogical classification and comparison to ground truth

Recent Accomplishments, cont.

- Developed evaluation plan for overall system
  - Lays out series of tests for both individual components and entire system
  - Metrics include rock and deposit classification accuracy, percentage of rocks found, power/memory requirements, etc.
- Evaluated plan quality improvements produced by planning optimization approach for interdependent goals
  - Extended past tests for centralized planner to collect statistics for distributed planning system
  - Each rover planner uses performs optimization based on randomized hill-climbing with restart
  - Shown to significantly improve plan quality in both single planner and distributed planner systems

Planning Optmization Performance



FY04 Directions

- Complete system evaluation
  - Evaluate classification accuracy of data analysis module vs. other approaches
  - Evaluate full system capabilities and limitations
- Perform several system demonstrations
  - Using environment and hardware simulators, show multiple rovers performing rock classification of local terrain area
  - Using rover hardware (e.g., Rocky 8, FIDO) in Mars Yard, show MISUS coordinating data collections w/ 2-3 rovers

MISUS: Multi-rover Integrated Science Understanding System

JPL

Problem:

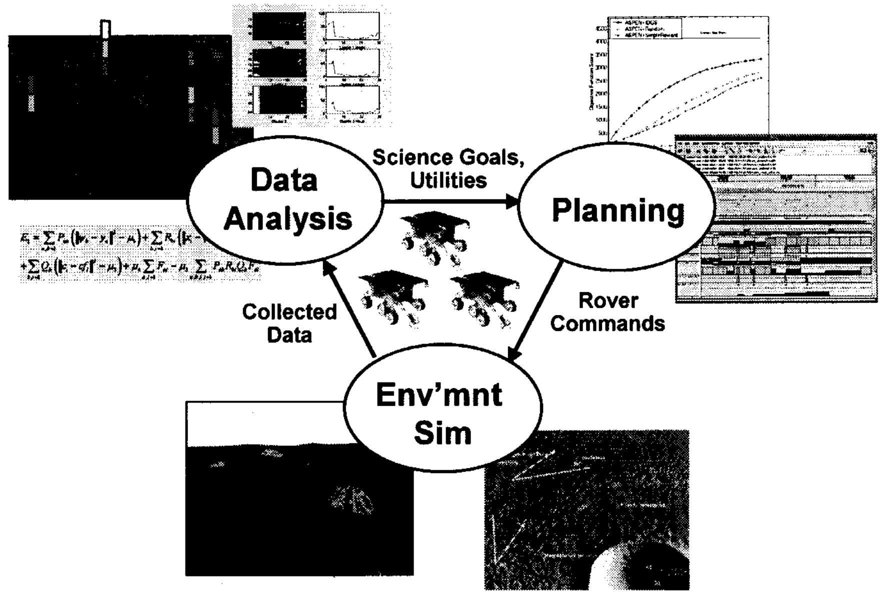
Enable a team of rovers to investigate a new planetary environment in a closed-loop, autonomous fashion with little communication from ground. In particular, develop onboard analysis and command sequencing capabilities to support robotic geological investigations.

Objectives:

- Integrate AI machine learning and planning techniques to provide closed-loop data collection, analysis and sequence generation.
- Intelligently coordinate multiple rovers in performing science operations both at command level and science analysis level.

Key Innovation:

- Developed a planning optimization approach for reasoning about and achieving interdependent goals in a distributed environment
- Design a machine-learning clustering algorithm to infer geological relationships among data and to produce new observation goals that improve overall model accuracy



NASA Relevance:

Relevant to future missions that require more autonomous and/or larger teams of rovers to gather and evaluate science data

Also applicable to spacecraft and constellation missions that would benefit from autonomous data collection and analysis

Accomplishments:

Developed distributed planning optimization approach for handling interedependent science goal information

Developed novel data-analysis algorithm for determining measurement uncertainty and science goal relationships

Papers presented at Mars Surface Workshop and Planning/Scheduling Workshop

Presentations to MSL & MDS teams on closed-loop data analysis and planning capabilities

Schedule:

Evaluate data-analysis algorithm vs. competing methods on data model accuracy and improvement over time – April 2004

Evaluate full system on series of metrics including rock classification accuracy, percentage of rocks found, power requirements, etc. - July 2004

Full system demonstration using multiple rovers to characterize rock distribution in local area. Will use multi-rover hardware and environment simulators. - Sept 2004

Extra Slides

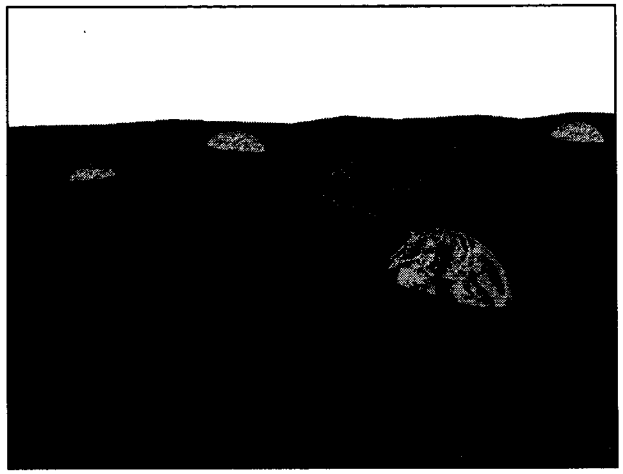
Science Data Analysis

- Models distribution of rock types in the observed terrain
- Uses a novel clustering approach that allows features to be treated heterogeneously
  - Employs an objective function for inferring geological relationships among data
  - Both spectral and visual texture data are analyzed
- A prioritization algorithm uses clustering output to generate a new set of observation goals
  - New information will further improve accuracy of data model
  - Select goals based on evaluation of scientific importance
- Prioritization examines goal interdependency relations
  - Individual goal values may by dependent on related goals being achieved
  - Algorithm generates goals, goal-utility values and goal interdependency relations

Planning

- Uses distributed version of CASPER planning system
  - Central planner develops abstract plan, dividing goals among rovers
  - Individual rover planners develop detailed, executable plan for achieving assigned goals
- Planning system can reason about interdependent goal relations
  - Evaluates goal interdependency relations when selecting subset of goals to achieve
  - Optimization based on randomized hill-climbing with restart
- Planning is dynamic
  - Rover planners monitor plan execution and perform re-planning when necessary
  - Uses rover simulation tool to provide execution feedback
  - Rover goals can be re-assigned to other rovers dynamically due to unexpected failures or resource over-subscription

Environment Simulation



- Simulates science data operations
- Different Martian rockscapes can be created
  - Select different rock types, size and spatial distributions
  - Currently use rock-patch-facies- deposit environment model to create terrain
- Mineral distributions developed in collaboration with JPL geologists
  - Currently using "rock-patch-facies-deposit" model to realistically create terrain
- Simulator executes science operations at appropriate locations and generates sample data
- Returns both spectral data and visual texture data