Combined EDL-Mobility Planning for Planetary Missions

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March 29, 2011
Outline

• Goals & Objectives
• Problem Statement
• Approach
  – Cost map
  – PDF
• Conclusions
Goals

• Develop data products that support decision making for coupled, multi-opportunity EDL/Mobility problems:
  – Site-specific decisions
  – Site selection motivated quantitative comparisons between different sites

• Provide an mission analysis/study tool for:
  – Systematic tradeoff between EDL and Mobility
  – Determining the relationship between selected Figure-of-Merits and key mission & system parameters
Framework for Coupled-Domain Mission Performance/Risk Analysis

Framework Elements

• End-to-end physics-based probabilistic models of performance
  ➔ Combined performance/risk analysis

• Coupled-domain trades/optimization
  ➔ Less over-design of the system for each phase/domain

• Principled mathematical approach
  ➔ Less likely to miss nonlinear performance/trade/effects

• High-fidelity models/simulations
  ➔ Defensible, quantitative results

Benefits to Mission

• Quantitative analysis/trades for more points in the architectural space

• Verify/optimize a cost-capped design for end-to-end performance/risk floor

• EDL/Rover System dependent (or independent) site-selection criteria

• Extensible to MSR-L MAV Ascent and MSR-O Orbital Rendezvous concept analysis

Pre-decisional – for Planning and Discussion Purposes Only
Objectives

- Develop a **probabilistic framework** that unifies consideration of EDL and Mobility performance
- Define **candidate EDL/Mobility problems** of interest to MSR concept studies and exercise the analysis framework
- Develop **interfaces to other study tools** and efforts (e.g. EDL Landing study/tools) so as to import data and probability distribution functions as needed into the MSR Study Tool
- Develop **extensions to the Multi-X concept** used in the EDL phase to take into account the subsequent mobility phase
- Develop **software to generate mobility related data products** to support the analysis
- Set up the **analysis capabilities for proposed MSR mission area**: 10km-by-30km
- Demonstrate **initial capability** at a coarser resolution i.e. computational improvements are possible but not the focus here
- Note that current focus is **not on the science data/sample acquisition phase** but on the landing and mobility trades associated with getting to/from the science/cache target.
• Sample Cache Rover (SCR) lands
• SCR drives to Science Target(s)
• SCR performs science & cacheing
• SCR drives to Cache Release / Rendezvous target & releases cache
• SCR continues on extended mission

• Sample Fetch Rover (SFR) lands
• SFR drives to Surface Rendezvous target
• SFR retrieves cache and returns to Lander
• SFR deposits cache into MAV
Proposed MSR Site Types

General Characteristics

Areoid

MSR Sites
Weathered away (exhumed) craters
Free of accumulated dust

“Go-To” Sites
• Holden Crater

“Sample-Locally” Sites
• Eberswalde Crater (hills with relief)
• NE Syrtis (rocky mesa edges, network of sand-dunes at angle-of-repose)

Land in safe region
Drive to science targets

Land in scientifically rich region while avoiding isolated bad spots

Pre-decisional – for Planning and Discussion Purposes Only
Hazards and Costs

Hazards
• For rovers - max drive slope, heights of rocks, terrain type
• For landers - max local slope at scale of lander diameter, hazardous rocks contained in lander radius sized circle

Cost-to-go
• For rovers – time, distance, wheel rotation with slip, obstacle proximity, risk penalty for hazardous/unknown regions etc., for moving from start to the nearest target
• For landers – safety of landing & consequences for subsequent mobility
Approach
Problem Statement

• Given
  – mobility hazards
  – landing hazards
  – landing PDF
  – science targets
  – vehicle parameters & initial conditions

• Place the SCR landing ellipse target so as to:
  – minimize the expected drive distance
  – meet failure probability constraints

Note the additional functionality beyond MarsLS - computing a risk probability that considers mobility activity after landing and finding of the best landing ellipse target placement.
Analysis Flow

- SCR mission sequence would be
  - Landing ellipse placement
  - EDL
  - Drive to target

- Planning goes backwards
  - Generate mobility cost-to-go map
  - Place multi-“X” for landing
  - Place a landing ellipse for landing

- Then, trade-off analysis
  - Simulate
  - Evaluate the performance
  - Change parameters/scenarios & repeat

- We will show 2D example w/ & w/o divert

Blue: Close to target
Red: Far from target
Cost Map Concept

Cost-to-go Map - A 2-D representation of decision making costs as a function of [x,y]

- Examples of decision making: "land at a good target point", "go to cache drop location target", "return to lander target location"
- Either directly used in the on-board decision making process or represents the effects of on-board decision making

Mobility Cost-to-go Map

- Captures rover path traversability (i.e. encodes the on-board path selection/planning navigation) to store cost-to-go from [x,y] to target

EDL Cost-to-go Map

- Add hazard cost for a landing target at [x,y] (binary thresholded to 0, ∞) to mobility cost (e.g. distance or time-to-go) from [x,y] to mobility target
Mobility Cost Map

Hazard lists (rocks, craters, sand dunes, etc.)

Hazard map (on a grid)

Trajectory search space

Graph Generation

Edge cost computation

Target (Science)

Shortest paths to the target

Close to target

Far from target
Mobility & Robotic Systems - 347

Mobility Cost Map – Hazard Data

- Circular rocks
- Each rock expanded by the rover radius

Hazard lists (rocks, craters, sand dunes, etc.)
Rasterize
Hazard map (on a grid)

Trajectory search space
Graph Generation
Edge cost computation
Target (Science)

Shortest-path spanning tree
Shortest paths to the target
• 8-connected graph
• 1m grid spacing
• Minimum costs to the target:
  - 0 (at the target)
  - $\sqrt{2}$
  - $1 + \sqrt{2}$
  - 3
8-connected grid

Error $< \frac{(1+\sqrt{2})-\sqrt{5}}{\sqrt{5}} \sim 8\%$

16-connected grid

Error $< \frac{(2+\sqrt{5})-\sqrt{17}}{\sqrt{17}} \sim 2.7\%$
Mobility Cost Map – Graph Generation

- Collision checks performed between rocks and each edge in path representation
Mobility Cost Map – Minimum Cost Path

- Hazard lists (rocks, craters, sand dunes, etc.)
- Rasterize
- Hazard map (on a grid)
- Trajectory search space
- Edge cost computation
- Graph Generation
  - Shortest-path spanning tree
  - Shortest paths to the target

- Used Dijkstra’s algorithm
- Encodes cost and path to be selected from any point to the goal
Minimum Cost-to-go Map

- Convert costs from points generated by Dijkstra into a continuous map representation
- Repeat this for each target & take the minimum
PDF Processes

**EDL Process**
- changes PDF by non-linear aero-flight and touch-down dynamics, sensor noise induced knowledge errors & atmosphere/wind disturbance induced delivery errors

**Mobility Process**
- changes PDF by traverse path kinematics and drive/turn mobility dispersions due to slip and navigation errors
PDF Calculation – Single Stage

Parameters
Nominal (P1)

Terrain Map (TM) → Cost Map (CM)

Parameters
Truth (P2)

PDF input
Terrain Truth (TT) → EDL or Mobility Process

PDF Output

• PDF’s may be User Prescribed; Analytically Derived; or Monte-Carlo Histogram Derived
PDF-Based Analysis

- **Use PDF to find expected values of key figure-of-merits:**
  - Mean landing fuel consumption under different Cost-Map logic
  - Mean rover traverse distance and traverse time
  - Expected mission life-time and distributions from PDFs of traverse-time and actuator time-to-failure, i.e. PDF of $t = \min(t_{\text{traverse}}, t_{\text{time\_to\_failure}})$

- **Determine sensitivity to key mission & system parameters:**
  - Divert distance (fuel requirement) -- Landing accuracy
  - Drive speed -- Actuator failure model
  - Hazard thresholds (for landing and for rover) -- EDL map size

- **Determine the effect of environments**
  - Science target distribution -- Hazard distribution

- **Derive key decision parameters:**
  - EDL targeting selection i.e. landing ellipse target placement
  - Optimum cache surface rendezvous target point

- **Analyze effect of information gained** from successive sensing of terrain (e.g., prefer to drive previously seen terrain)
Available Mars Data Products

- **Stereo Elevation Maps** (HiRISE)
  - Kirk (USGS)
- **Rock Density Maps** (HiRISE)
  - Huertas
- **Material Properties Maps** (THEMIS)
  - Golombek
- **Visual Terrain Classification** (HiRISE)
  - Bellutta
- **Slope Maps** (HiRISE, USGS DEMs)
  - Kipp/Bellutta
• Rock list
  – Image frame
  – Circular obstacles
  – 76,874 rocks in 5km-by-26km region

• Slope map
  – Geo-registered
  – Grid @1m resolution

• Registration error
  – Linear translation
  – Linear rotation
  – Other terms (neglected)
EDL without Divert

- Hazard list
- Dilate by lander radius
  → Lander treated as a point

Landing hazard map
(white = above threshold)

Weighted sum
Landing PDF
Landing failure probability
for each ellipse center
EDL without Divert - Landing Ellipse Placement

Mobility cost-to-go map

For each safe landing ellipse center, evaluate the expected CTG & landing failure, then pick the best ellipse

Landing failure probability

High risk

Thresholding

Low risk

Close to target

Far from target
EDL Taxonomy

Without Divert

Entry → Parachute

Ignition ellipsoid

Landing ellipse

With Divert

Entry → Parachute

Divert ellipse

x: safe landing target

Landing PDF
• Map is iteratively used during parachute descent together with instantaneous **reachable footprint** of powered descent system to select & divert to landing target
• Map is simplified to a discrete set of landing targets “X” to simplify on-board, real-time use
• Lowest cost & reachable landing target is selected during parachute phase

**On-Board EDL Cost Map**

**Successive reachable areas during parachute phase**

Cost map covering landing ellipse

**Multi-X With Costs**

Pre-computed list of targets with costs.

Target list distribution is dense enough to guarantee at least one target within reachable zone.
EDL with Divert

- Start from the same hazard map
- Can divert to any point within the divert ellipse
- Divert capability expands the safe landing region

Color: safe
White: unsafe

Best value
EDL with Divert - Ignition Ellipse Placement

Ignition PDF

Landing failure probability for each ignition ellipse center

‘X’s are assumed to be densely populated
EDL with Divert - Landing Ellipse Placement

Failure probability map

Mobility cost-to-go map

Threshold at accepted failure probability

Best landing ellipse
With and Without Divert

Distribution of rover drive distance

- Significant reduction with divert (90% in this example)
Representative Paths

Without divert

With divert

Target
Conclulsion

• Extended **PDF methodology** familiar in EDL analysis to end-to-end Mars Rover mission using probability chains

• Introduced **Cost Map** concept as a unified method for describing staged decision making in EDL and Mobility

• Built a cost-to-go map for EDL use that captures a **key coupling between EDL & Mobility**

• Developed techniques select best **Landing Ellipse Target** based on both EDL & Mobility performance

• Future work
  – More realistic EDL model
  – Address **scaling and computational** issues - handling of large data sets, optimizing map resolution, adding user provided heuristics
Questions / Discussions