Keck Institute for Space Studies
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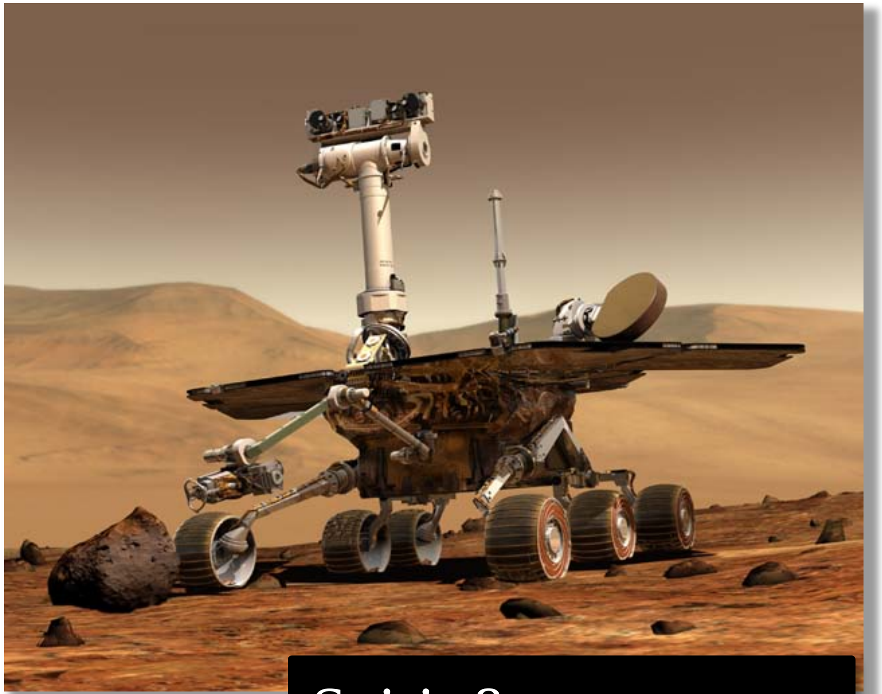
DuAxel Mission Architecture for Accessing and Sampling High Risk Planetary Terrains

Issa Nesnas(JPL), Joel Burdick (Caltech)

Motivation
Mars Rovers

Sojourner
1997



Spirit &
Opportunity 2003

Curiosity
Launched 2011

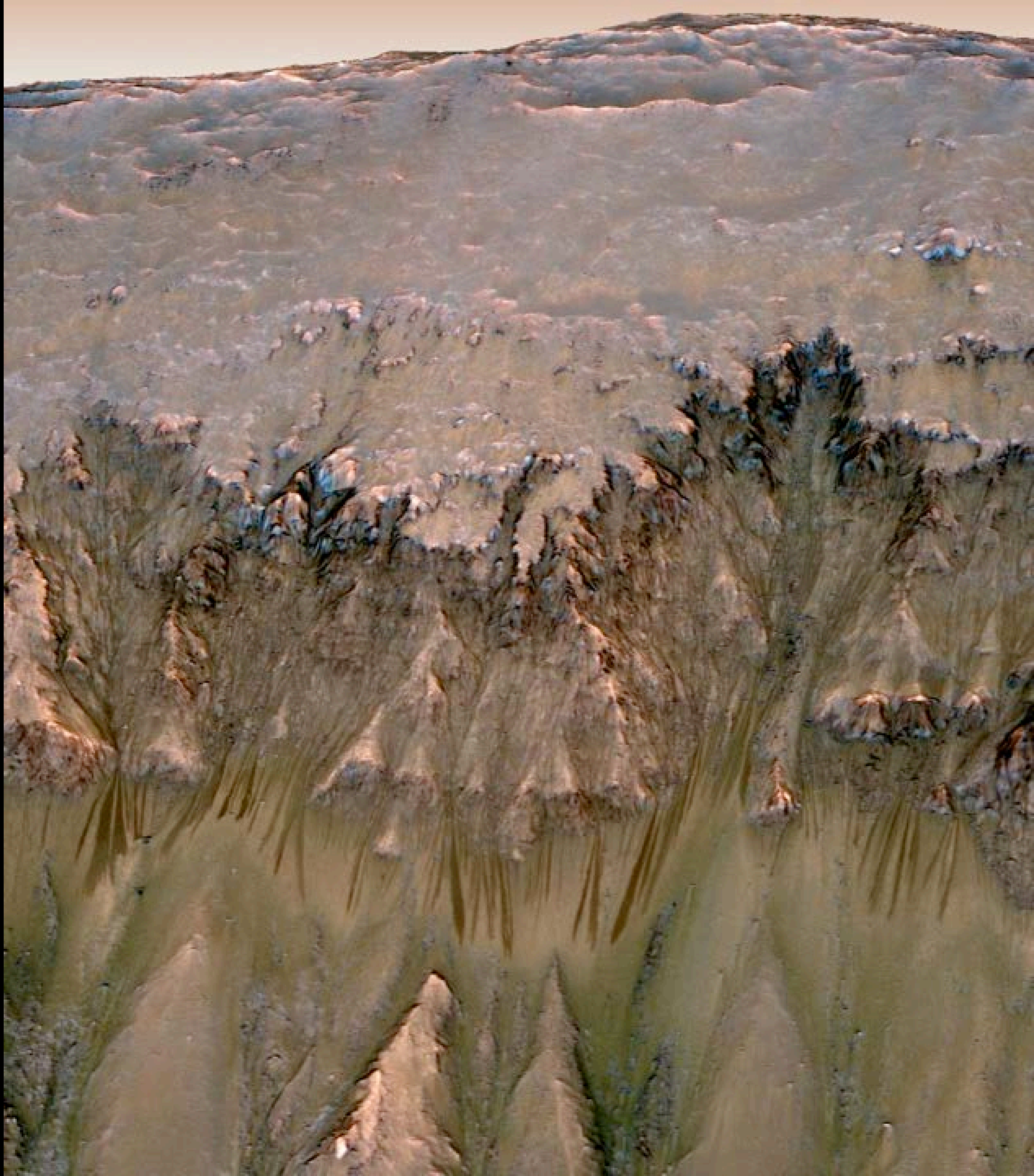
Mars

Recurring slope lineae (RSL) appear during warm seasons

Putative brine outflows

Narrow flows
0.5 m – 5 m
On steep slopes
25° – 40°

Credit: Mars Reconnaissance Orbiter
HiRISE - August 4, 2011



Mars

Cape St. Vincent, Victoria crater

Exposed Strata

Near vertical cliffs

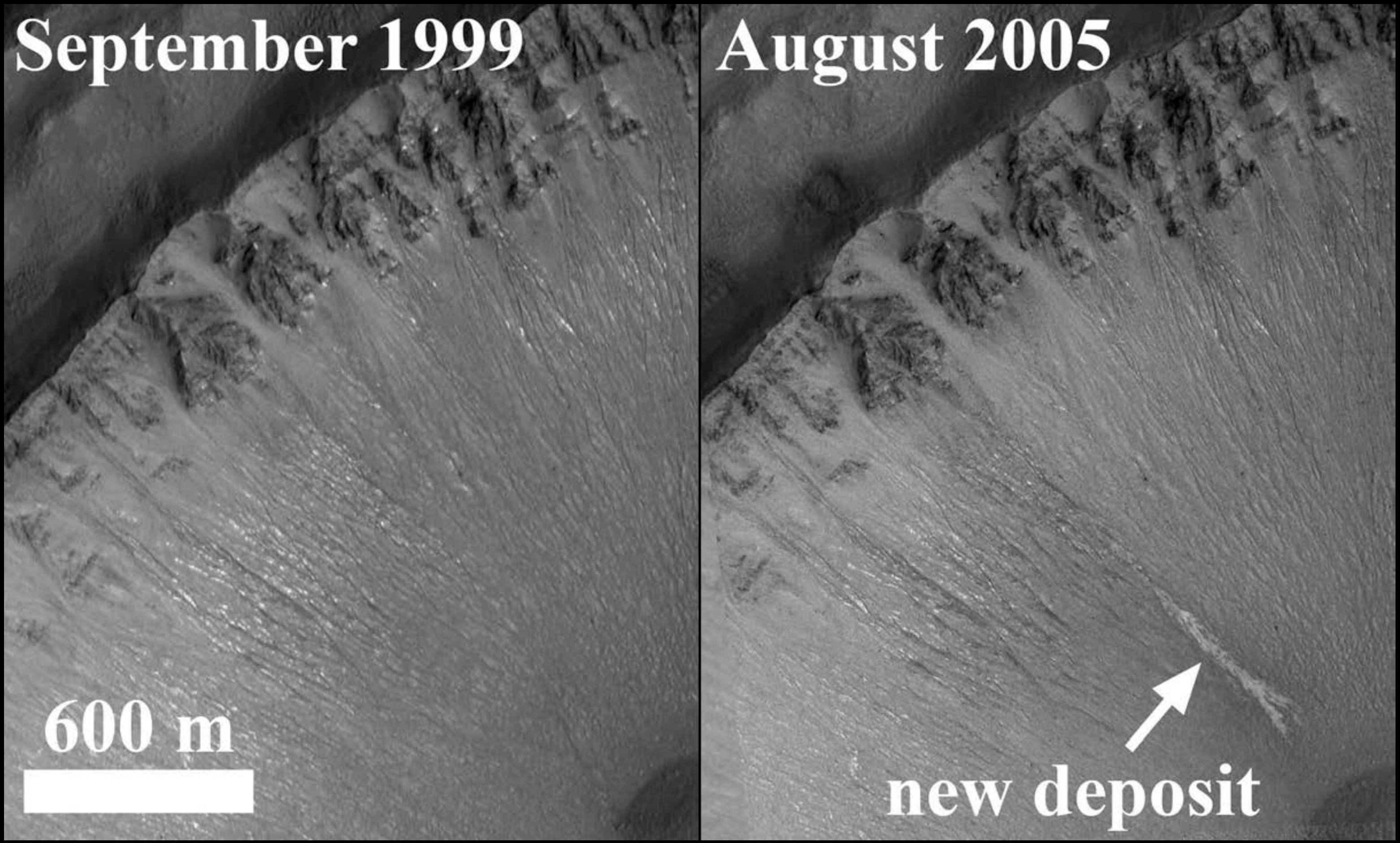
False color

Credit: MER – Opportunity Rover

Mars

Fresh geological flow on crater wall.

~1km down ~40º slope



Unnamed crater in Centauri Montes region on Mars.

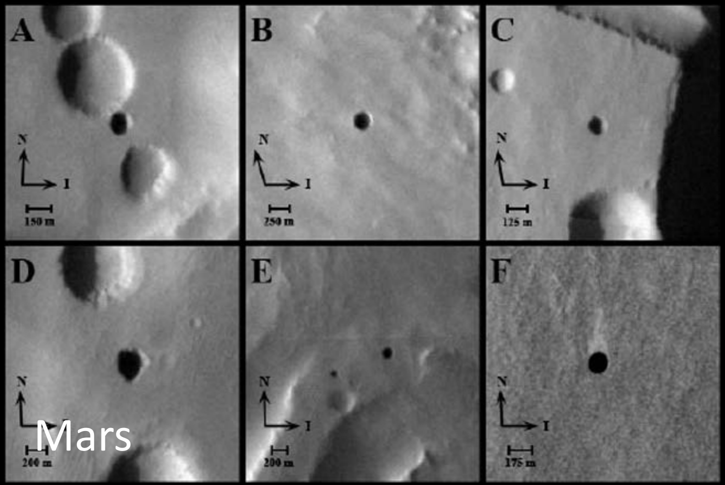
Credit: Mars Orbital Surveyor

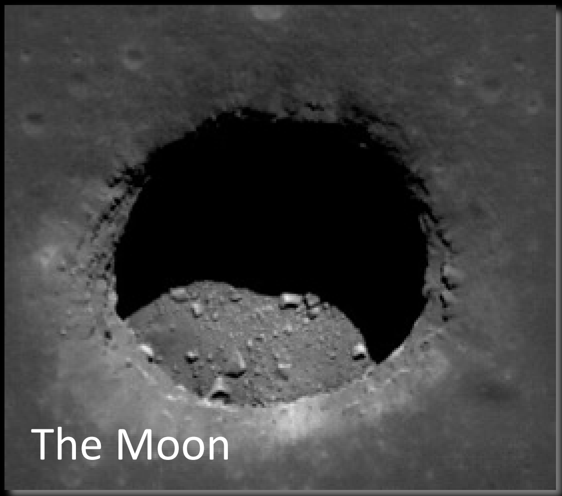
Mars
The Moon
Earth

Dark spots believed to be caves

Vertical walls
No surface of repose

Credits:
- (Mars) G. Cushing, et al, (2007), THEMIS observes possible cave skylights on Mars, Geophysical Research Letters, 34
- (Moon) NASA/GSFC/Arizona State University
- (Earth) USGS, Hawaii and Arizona

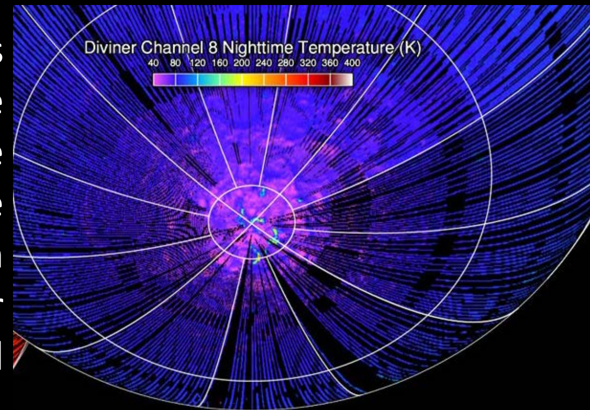


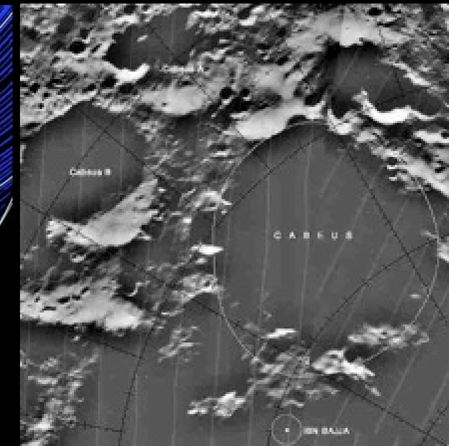


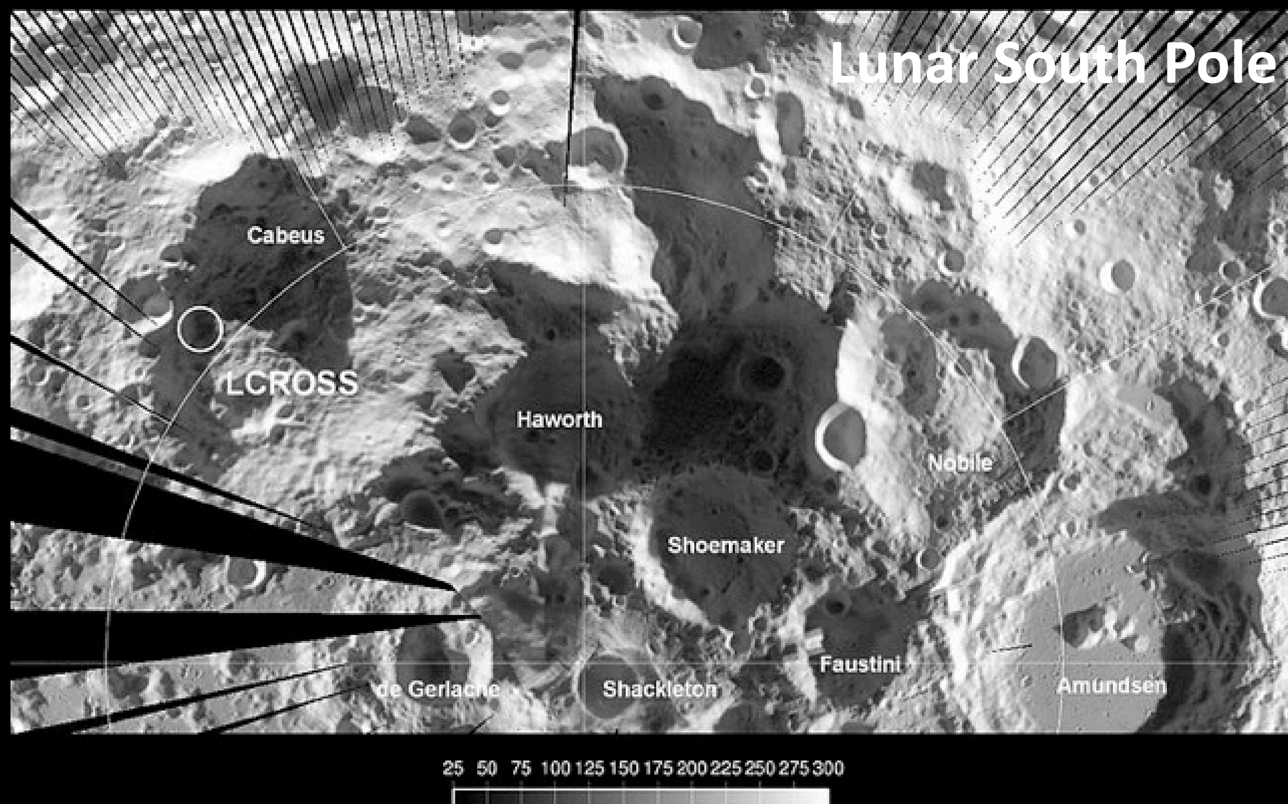
The Moon

Evidence of water ice

LRO's nighttime temperature survey of the lunar south pole by Diviner shows cold traps.







Diviner Channel 8 Brightness Temperature Map (K)

Heavily cratered surface and cold traps (deposits within craters)

Cold traps temperatures 40 K – 70 K

Credit:

- Lunar Reconnaissance Orbiter – Diviner

Rovers for extreme terrain.

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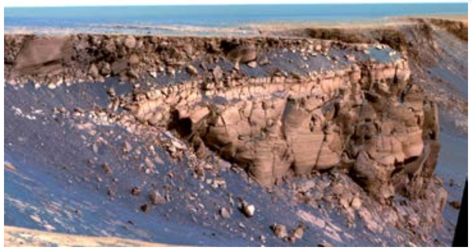
Design challenges

Steep slopes & uneven terrain



Lack of direct sunlight

Deformable soil

Disrupted communications

Large rocks/obstacles

Extreme cold

Early Related Work

Jet Propulsion Laboratory
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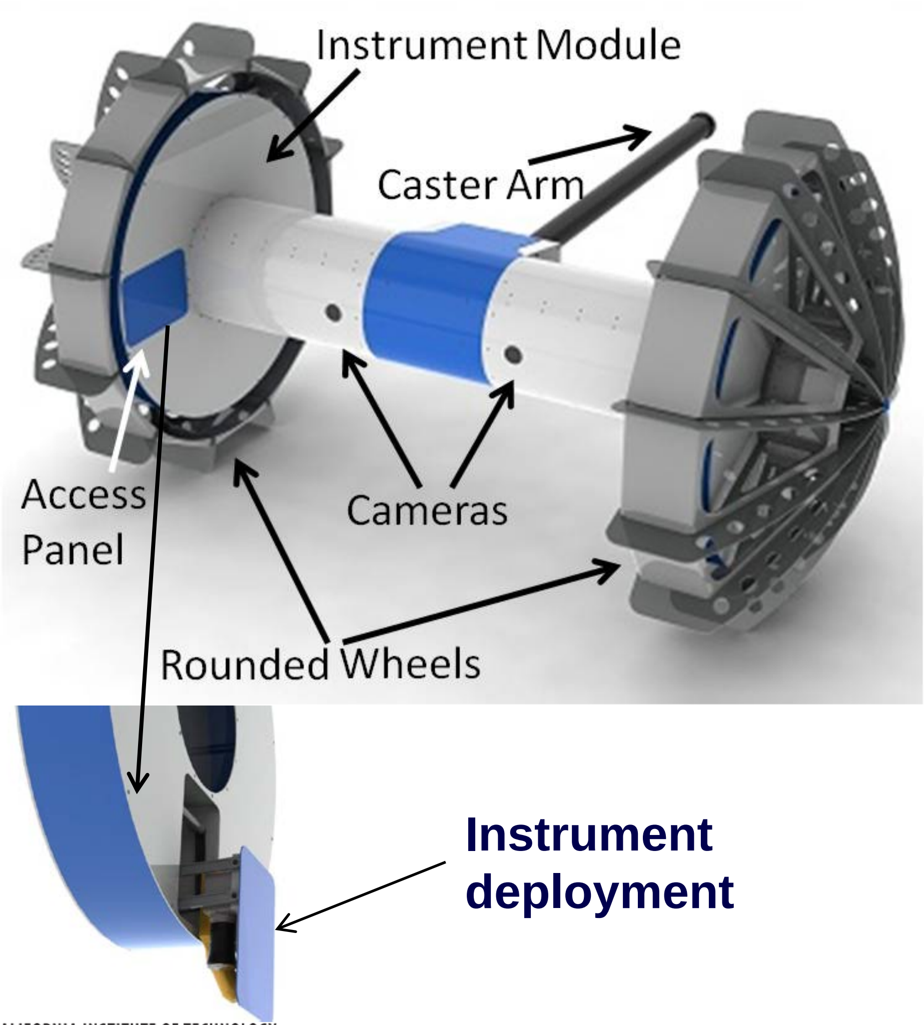
Cliff-bot
- Tethered wheeled robot.
- Two anchor-bots support winches
- Recon-bot observes/reports obstacles.
- Winching from above causes tether abrasion.

Dante II
- Tethered walking robot.
- Robot-side winch.
- Explored Mt. Spurr in 1994.
- During ascent, fell on its side and was unable to right itself.

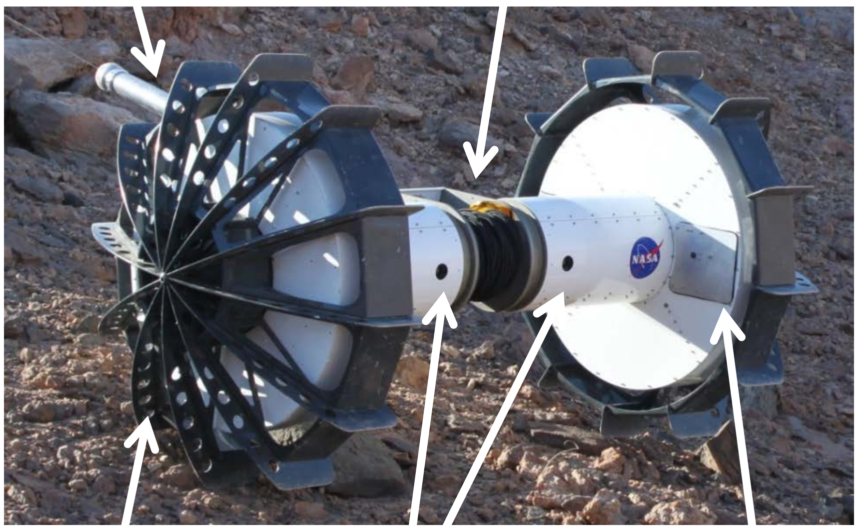
Axel Concept Design



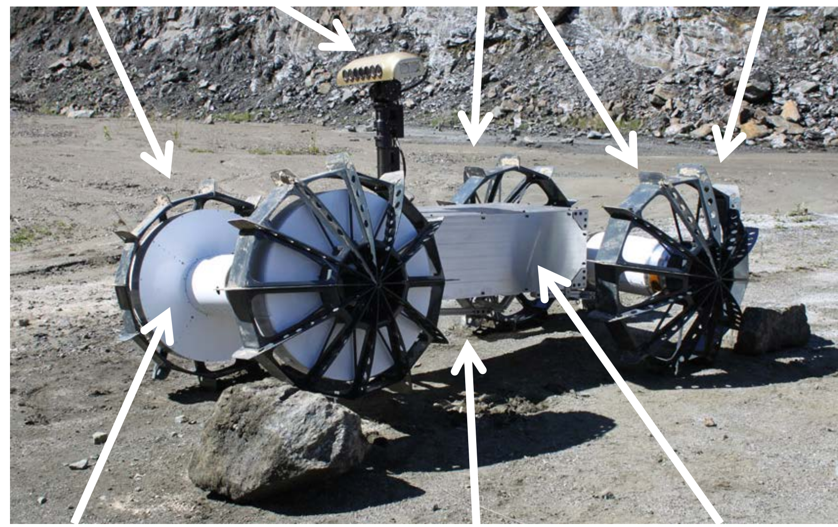
- **Versatile Mobility**
  - Operates with and without a tether
  - Traverses/rapels extreme terrain
  - Grouser wheels overcome large obstacles
  - Robust: operates upside down
  - Simple: minimally actuated
- **Science Capability**
  - Accommodates multiple instruments
  - Points individual instruments
  - Has favorable payload to system mass

The Axel/DuAxel Rover System

Axel

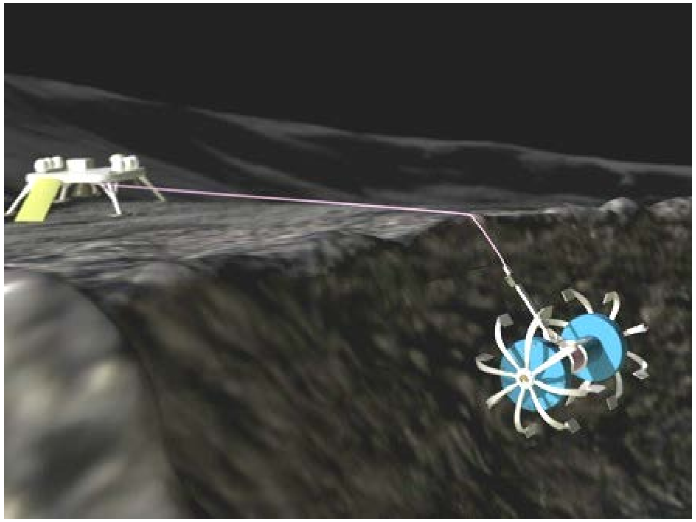


DuAxel

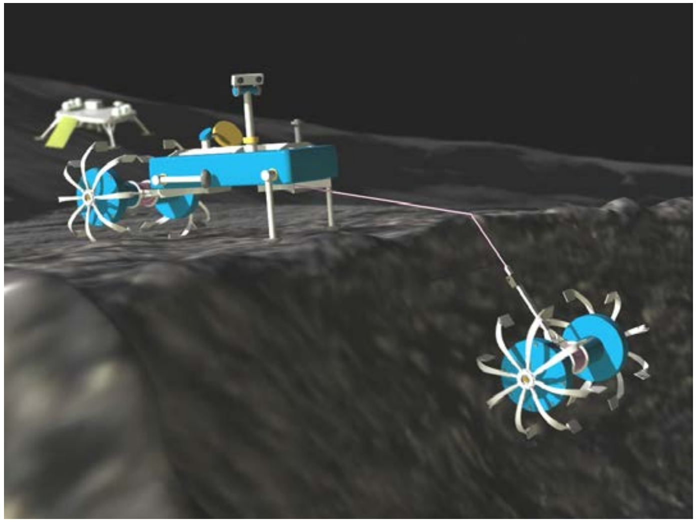


[Abad-Manterola et al., 2011], [Nesnas et al., 2012]

Mission Integration Options



Axel - Fixed mother (lander)mobile daughter (Axel)

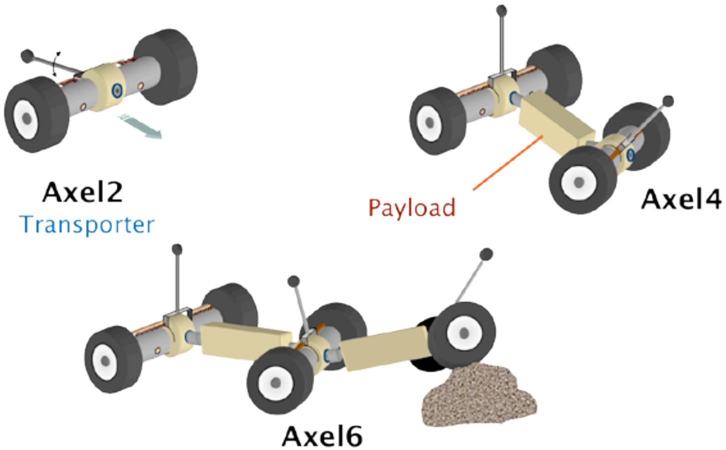


DuAxel - Mobile mother Mobile daughter (two Axels)

Axel – payload on larger rover

Brief History

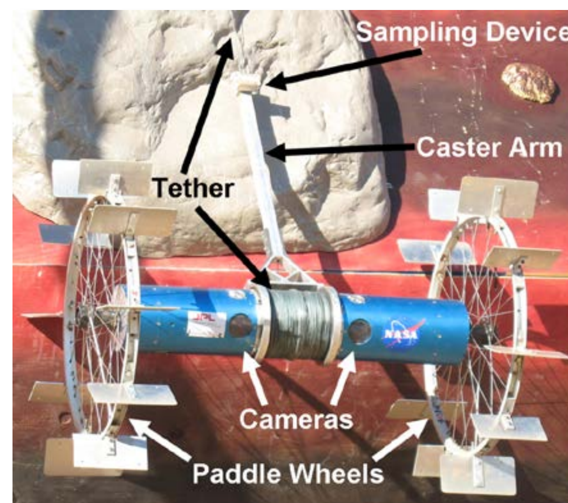
Original Concept (1999)



Key Concept – separate **payload** from **transporter**

1st Prototype Rover (2002)

1st Tethered Prototype



1st Grouser Prototype (2009)

Axel 2 and DuAxel

Arizona Desert—June 2011

Arizona Field Test Movie Here

Potential Impact/Payoffs

1. Single Axel can be built at reasonable cost
2. Axel can be readily reconfigured for different missions
3. DuAxel is a self-contained, lower cost mission architecture which can achieve science goals of conventional rover, with bonus of extreme terrain access.
4. DuAxel allows for sustained duration exploration of craters and low terrain (where little/no sunlight available)
   - Thermal analysis shows Axel can survive long duration in coldest temperatures measured in solar system
5. Novel sampling/measurement on cliffs/slopes

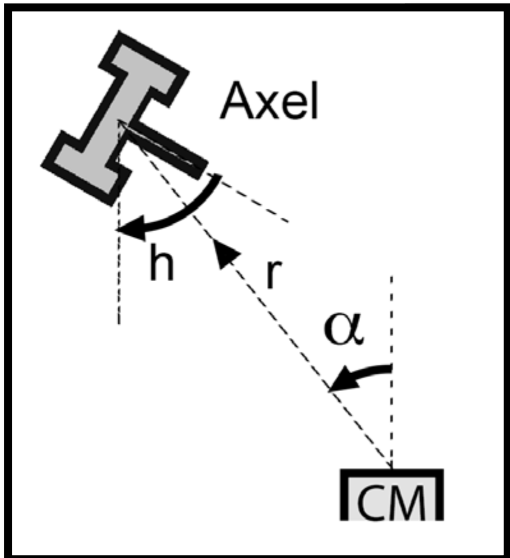
Overall Goal of Project

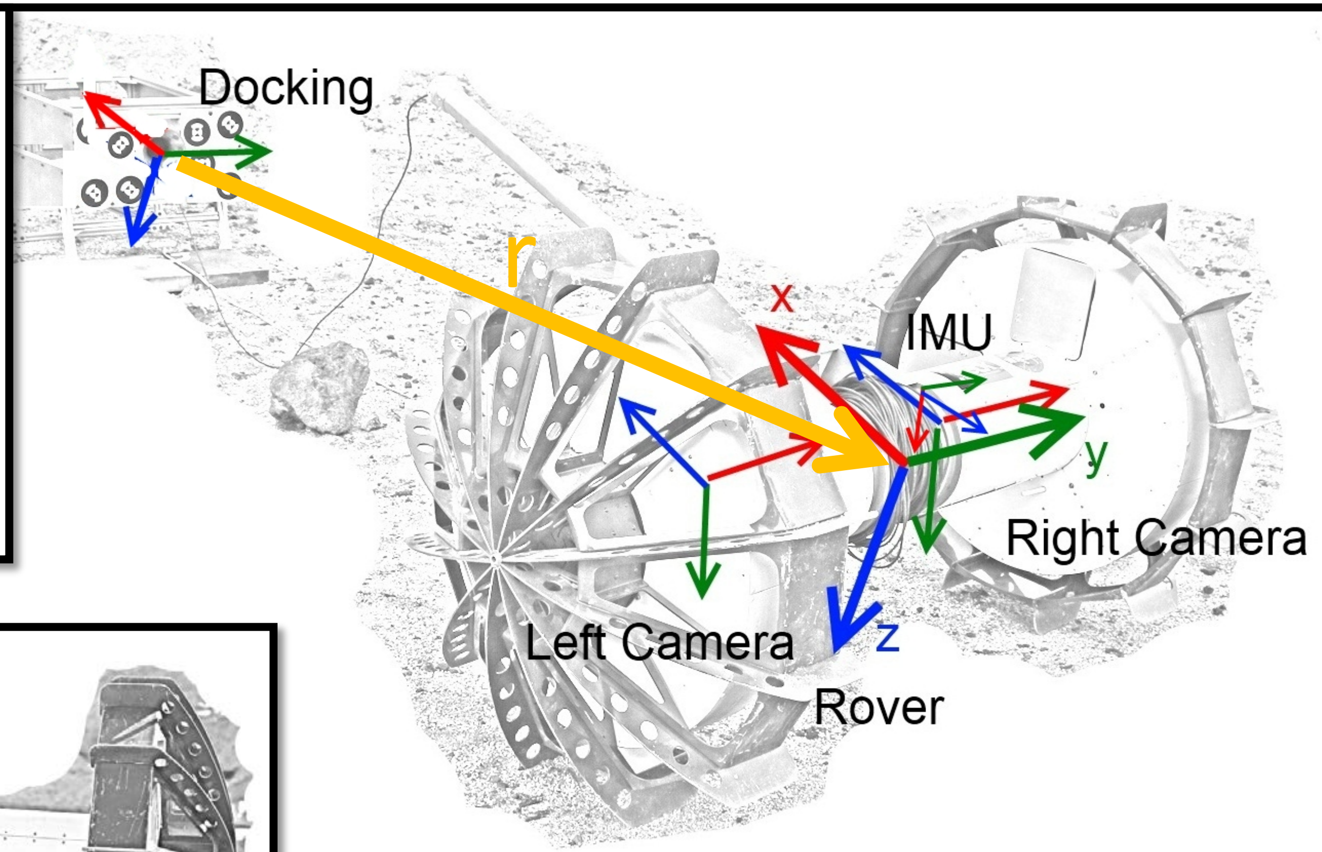
Develop, demonstrate autonomous control and operation of Axel/DuAxel in extreme conditions.

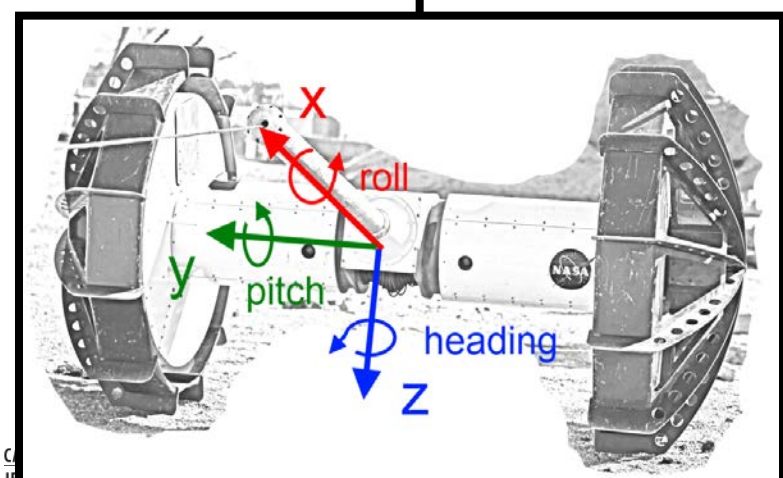
- Under mission-like constraints of remote planetary exploration.
- Using robot's on-board sensor suite

- Provide science/flight communities with a credible demonstration of Axel/DuAxel and data for evaluation
- Eliminate/mitigate perceived risks with this architecture.

Docking Framework (Dorian Tsai)



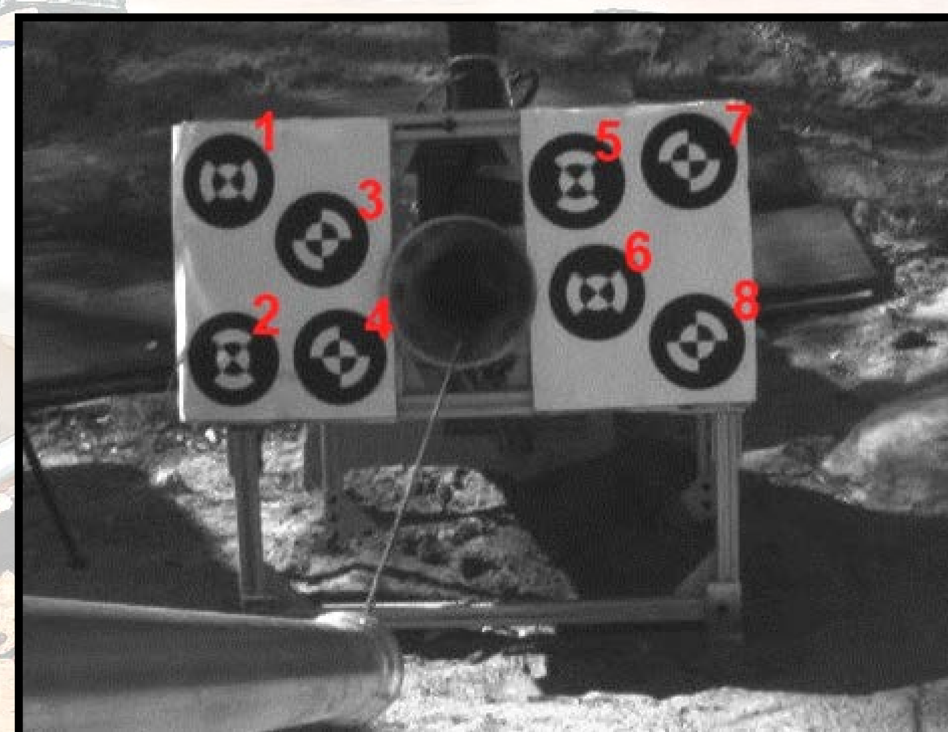




conventions

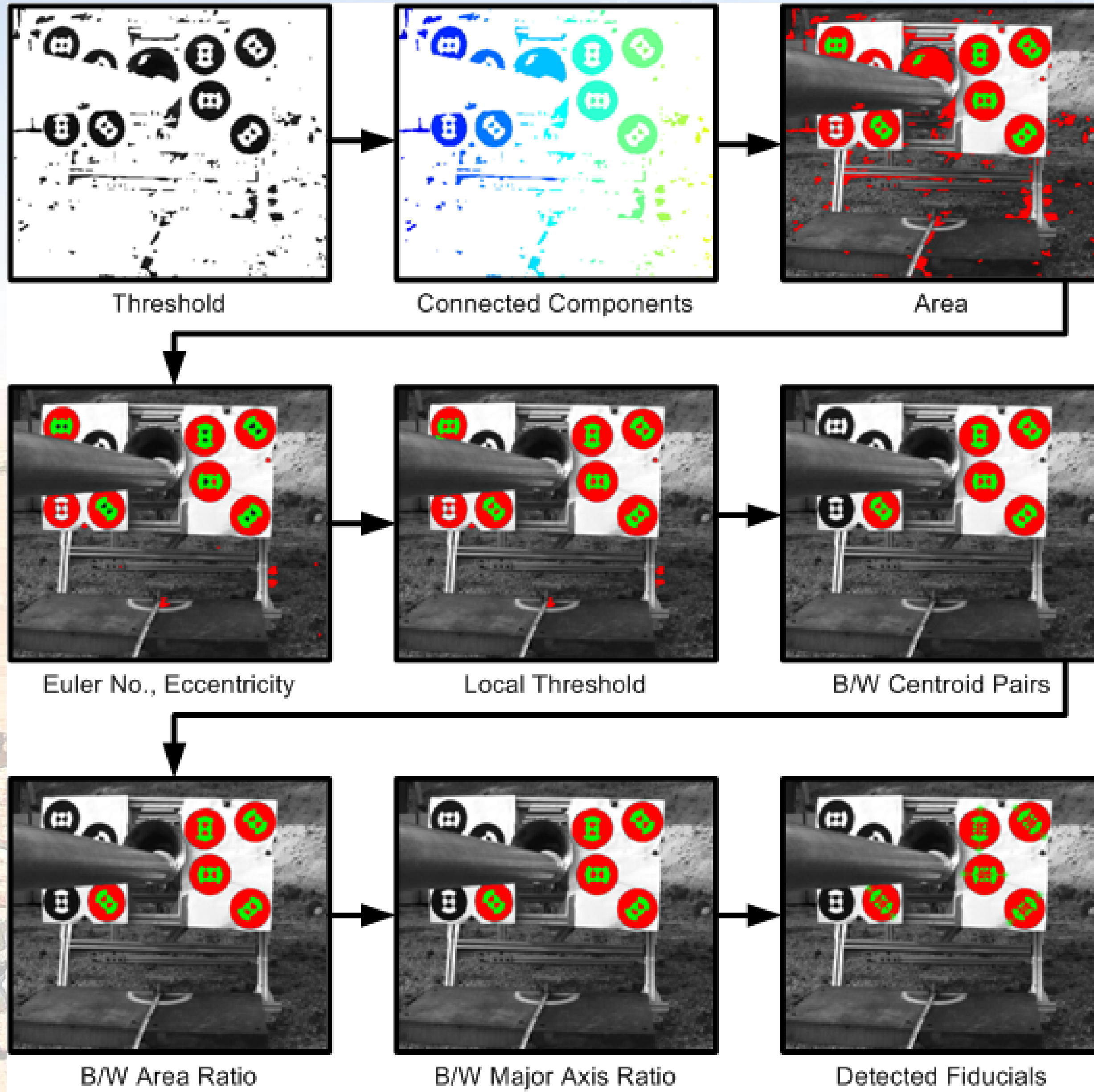
Fiducial Design

- Black & White
  - Maximize contrast
- Circular
  - Invariant centroid
- Black border for detection
- 5 cross hairs
  - Corners, human ID, pose
- Many unique properties for detection/blob analysis
- Constellation of 8
  - Asymmetry
  - Pose, handle occlusion
- Orientation for ID



Fiducial Detection Process

- Developed using real images
- Based on blob analysis
- Apply constraints to eliminate fiducial candidates

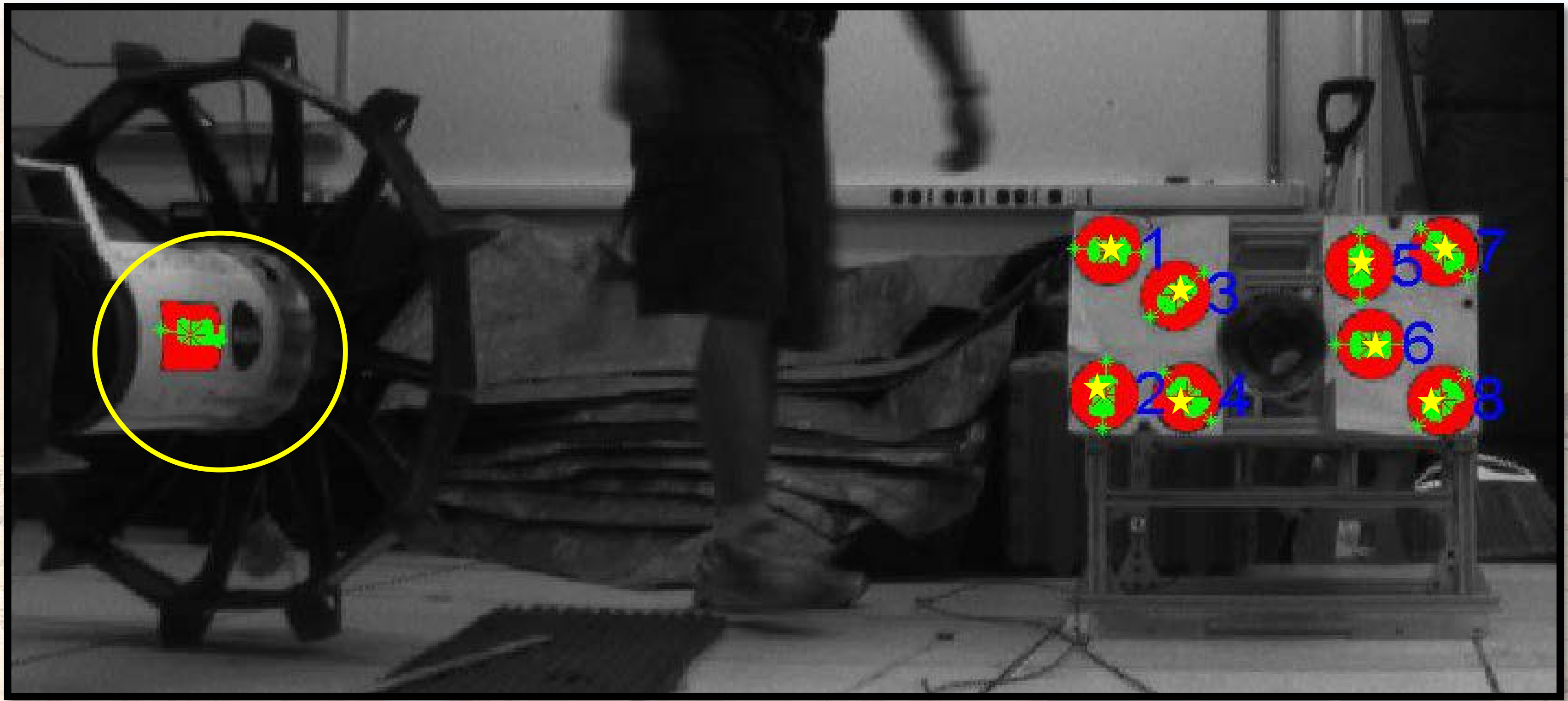


Fiducial Correspondence

- Fiducial orientation to prune possibilities → 16
- RANSAC approach with homography reprojections
- Correspondence with minimal image reprojection error
- Handles occlusions and false detections

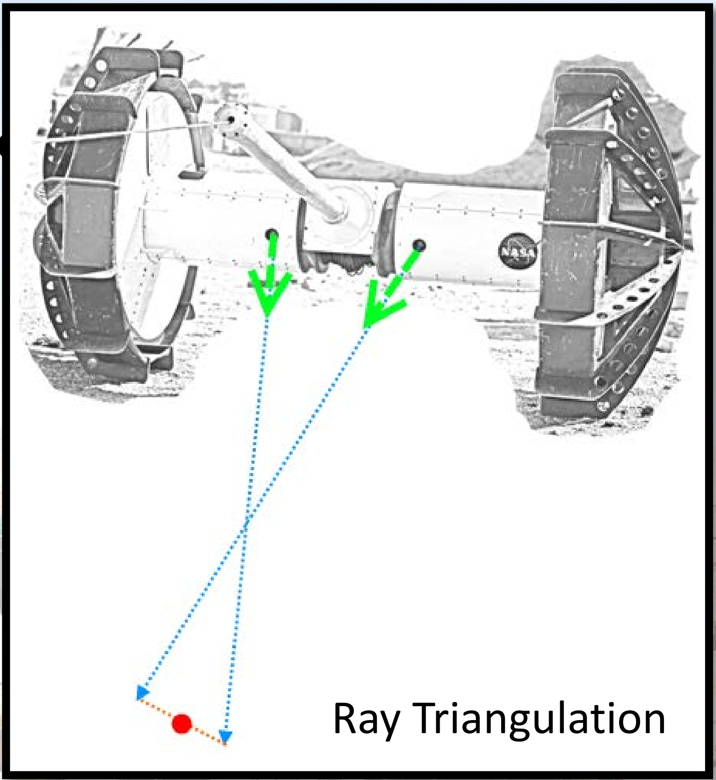
Fiducial Correspondence

- Model reprojection correspondence to measured fiducials based on closeness threshold
- Outside threshold assumed false detection



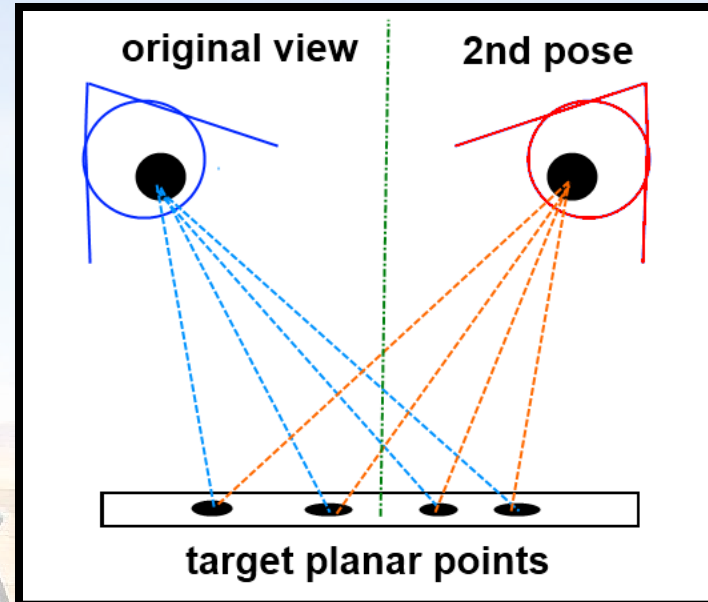
Pose Estimation – Point Stereo

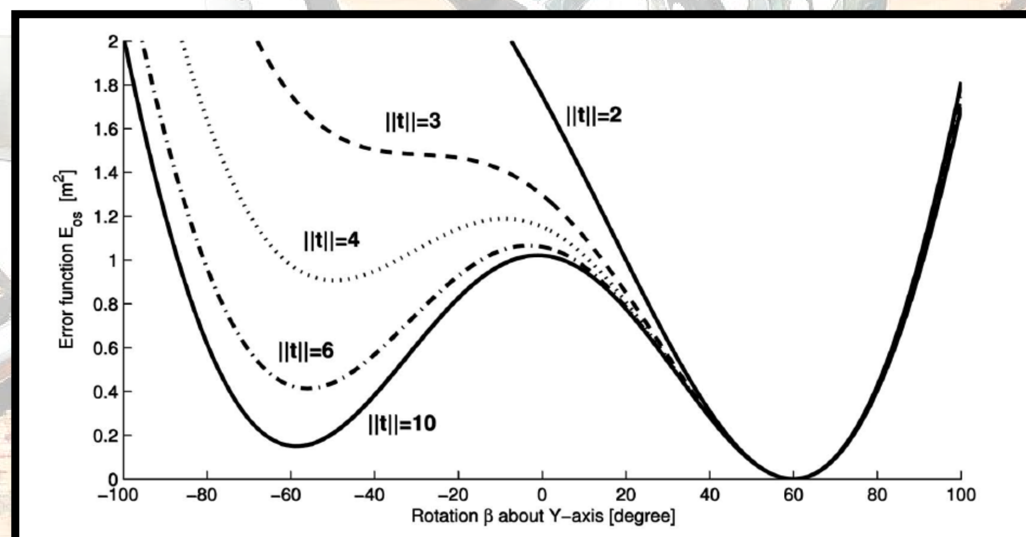
- 8 corresponding image points
  - Measured / Homographic reprojecti
  - Mix does add some error
- Triangulation, depth estimation → 3D points
- Combining 3D points into relative pose
  - Nonlinear LS Optimization
    - Initial estimate: mean 3D pts
    - Transform model to 3D pts
    - Match to 3D pts better captures heading than image reprojection
    - Objective: $err = \sum \sqrt{(x_{fid} - x_{ls})^2 + (y_{fid} - y_{ls})^2 + (z_{fid} - z_{ls})^2}$



Pose Estimation - Mono

- To handle large turns
- Robust planar pose algorithm (Schweighofer & Pinz, 2006)
- Error function has 2 local minima
- Find 1 via mono pose estimation based on collinearity (Lu, Hager, Mjolsness, 2000)
- Analytically find 2nd sol.
- Choose lower object space error

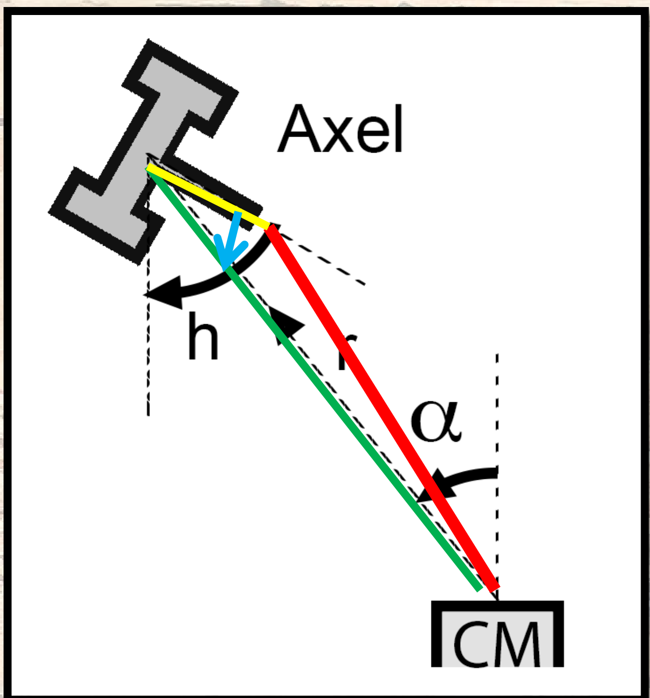


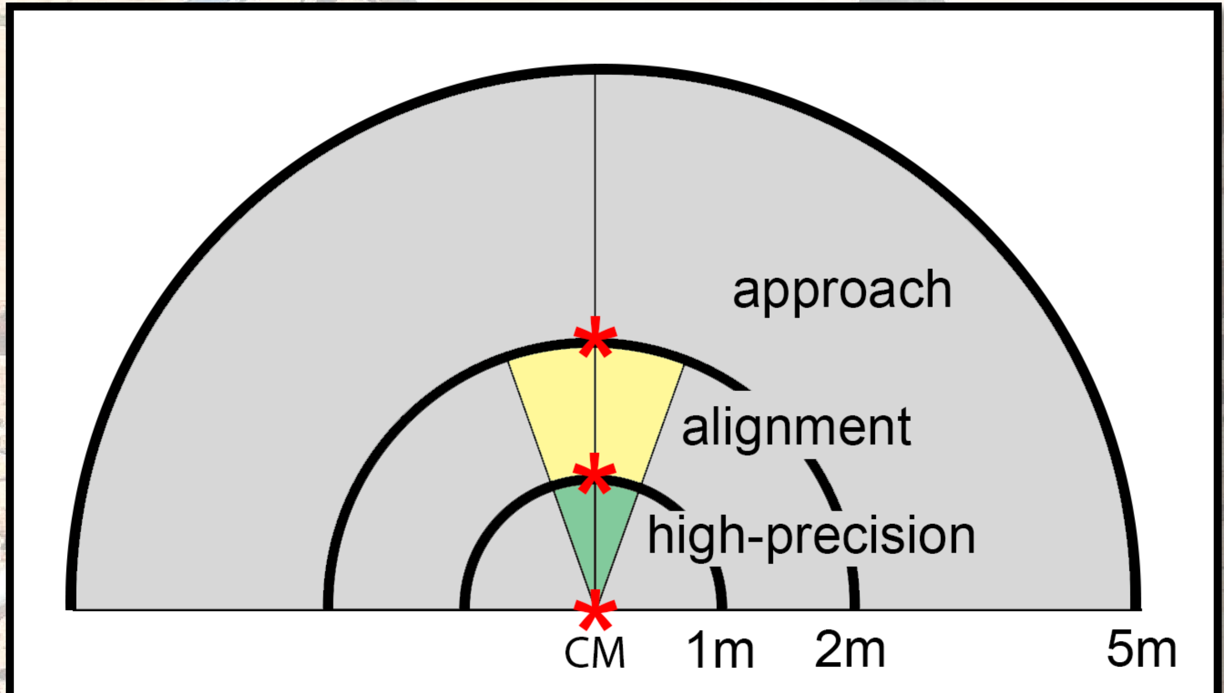


- Only CAHV model
  - Expect error due to lens distortion

Docking Problem

- Assume flat terrain
- Position (x,y) or (r,α) and heading
- Taught tether
- No obstacles
- Docking regions from manual testing
- Simple approach

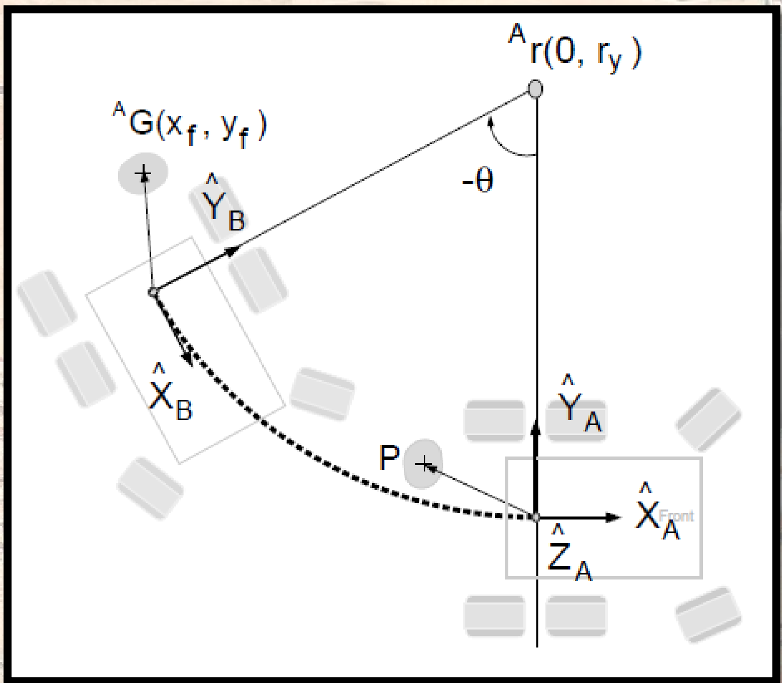


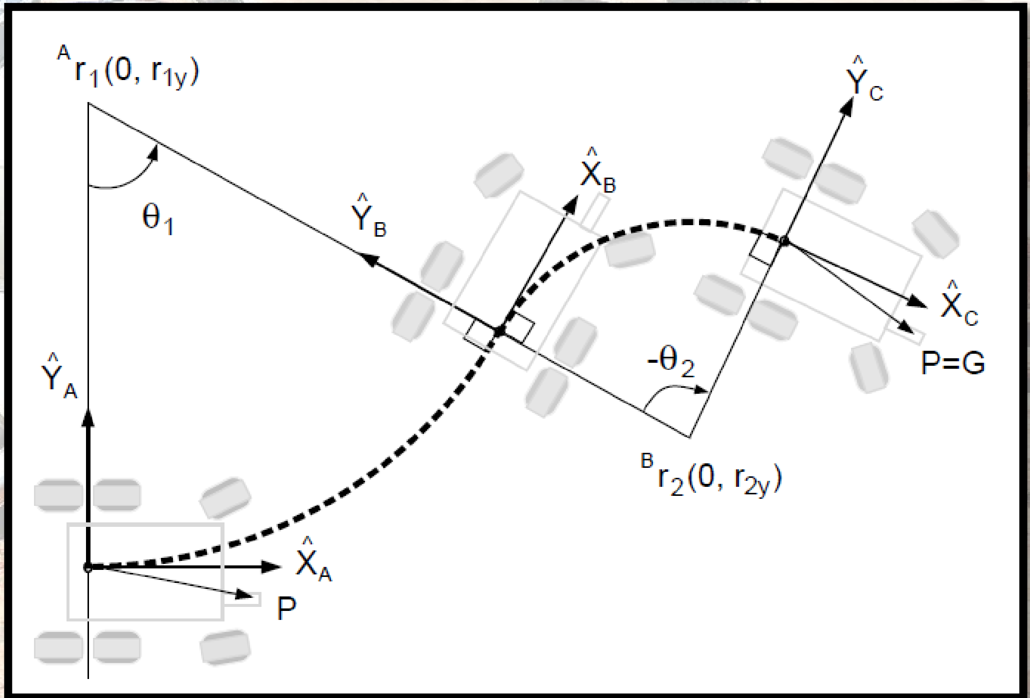


Path Planning Arcs

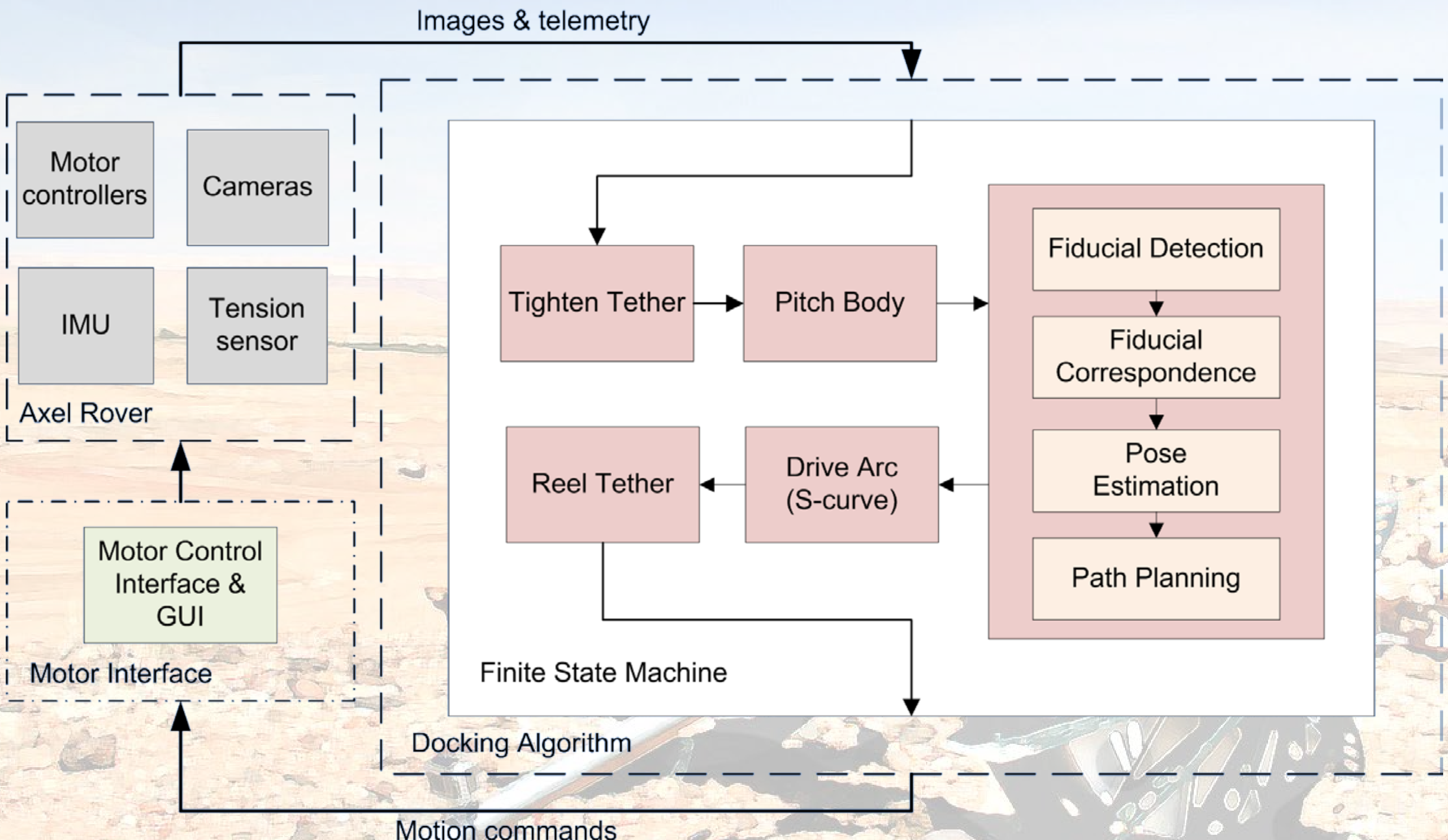
- 1 arc: position
- 2 arcs: position and orientation
- Objective: $\eta(r_{2y}) = |r_{1y}\theta_1| + |r_{2y}\theta_2| + (||r_{1y}\theta_1| - |r_{2y}\theta_2||)$

Arc lengths   Sharp curves





System Overview

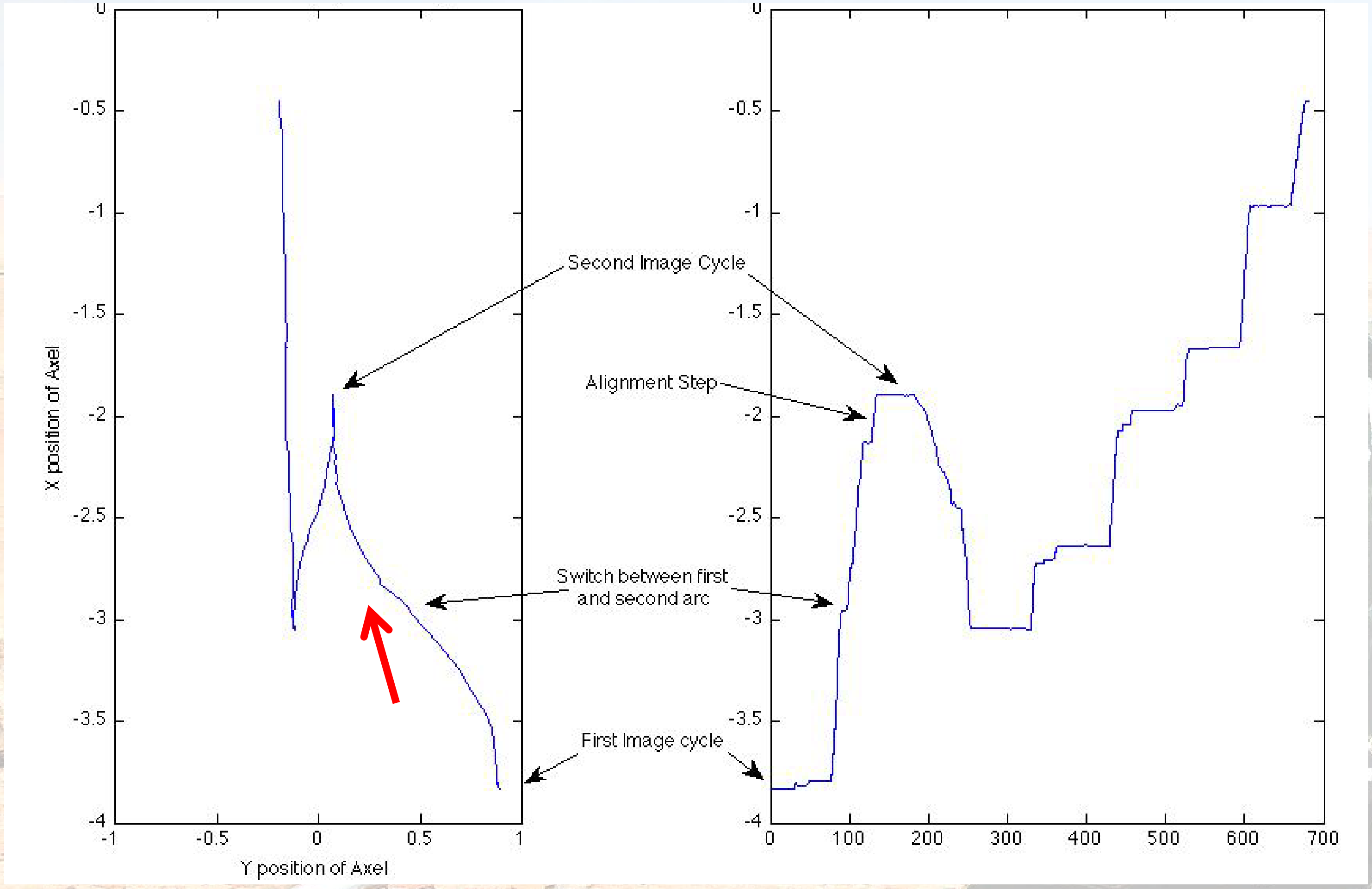


Experiments

- To demonstrate functionality, test operational limits
- On hard ground and soft sand
- Vicon for ground truth
  - 6 DOF pose relative to central module (CM)
  - Noise ~1mm with good coverage

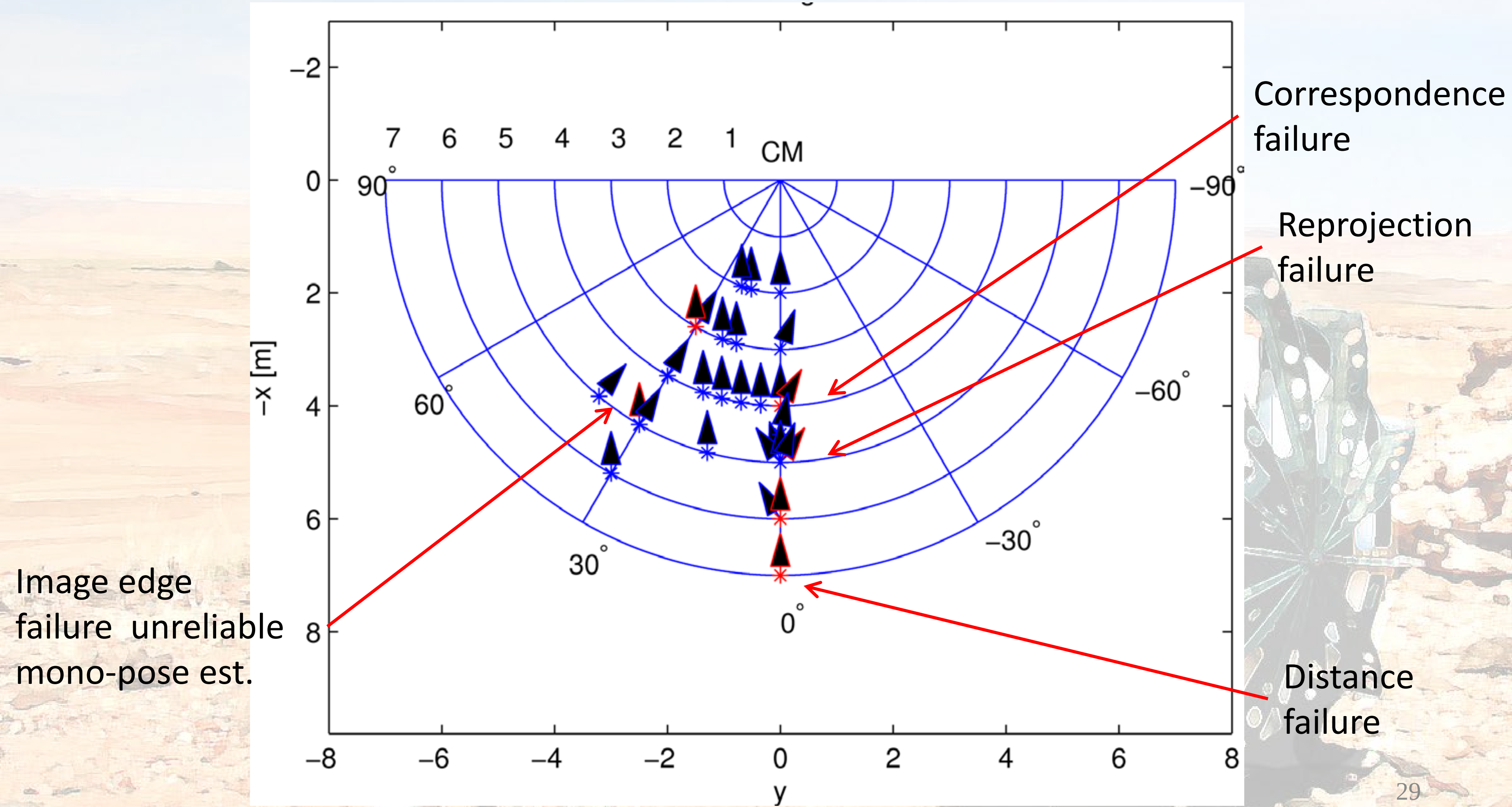
Typical Docking

- Vicon X,Y(m) data X(m) vs. time (s)



Preliminary Results

- 40 tests, 29 successful

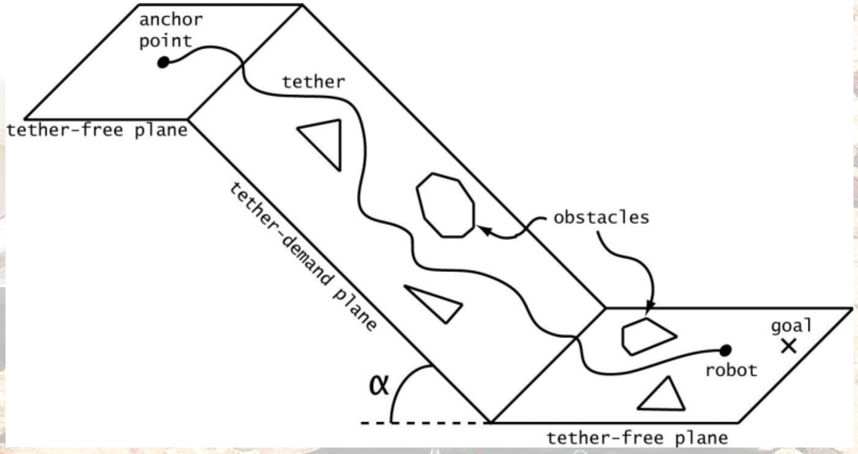


The Tether Planning Problem

- Plan a safe ascent-descent path pair around obstacles.
- Map knowledge incomplete -> Use online planning.

Assumptions

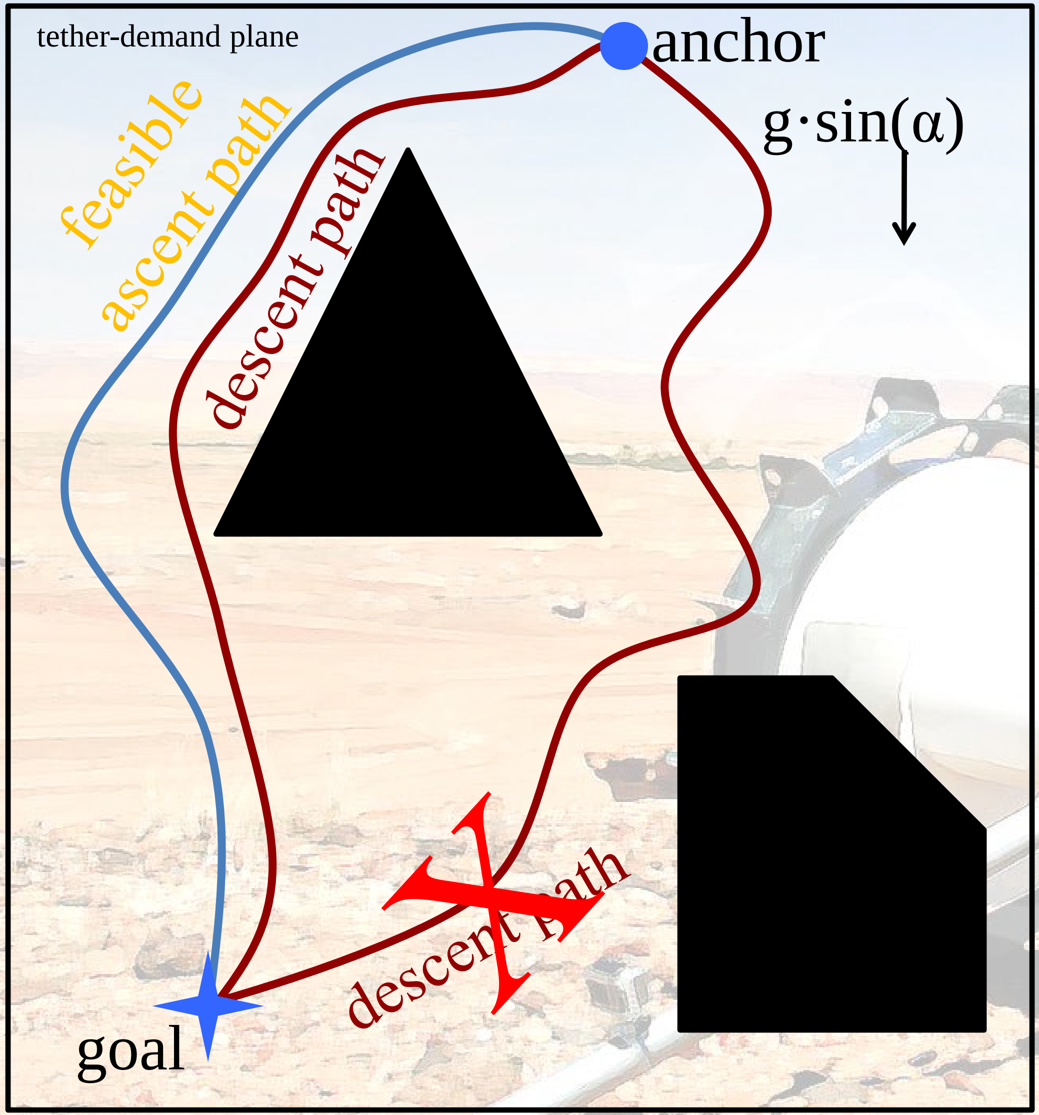
- Quasi 2-dimensional terrain, consisting of tether-demand and tether-free planes
- No tether friction



[Hert and Lumelsky, 1995, 1996, 1998, 1999], [Xavier, 1999], [Abad-Manterola et al., 2011], [Abad-Manterola, 2012]

Tethered Motion Planning

Avoiding Engtanglement

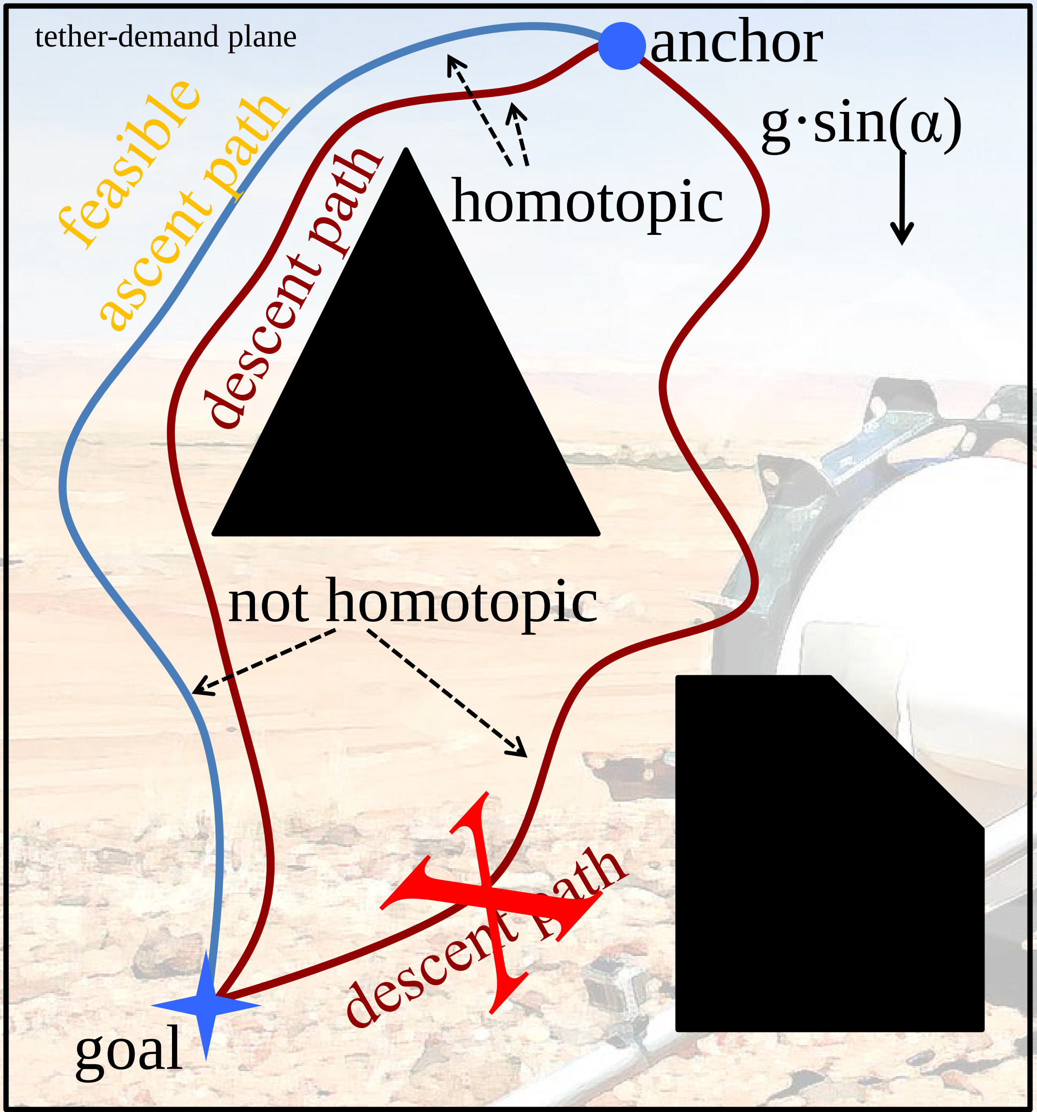


Key Considerations

- Need to compute a round-trip path.
- Need to avoid tether entanglement.

Tethered Motion Planning

Avoiding Engtanglement



Homotopy
A continuous deformation between two continuous paths (without encountering an obstacle).

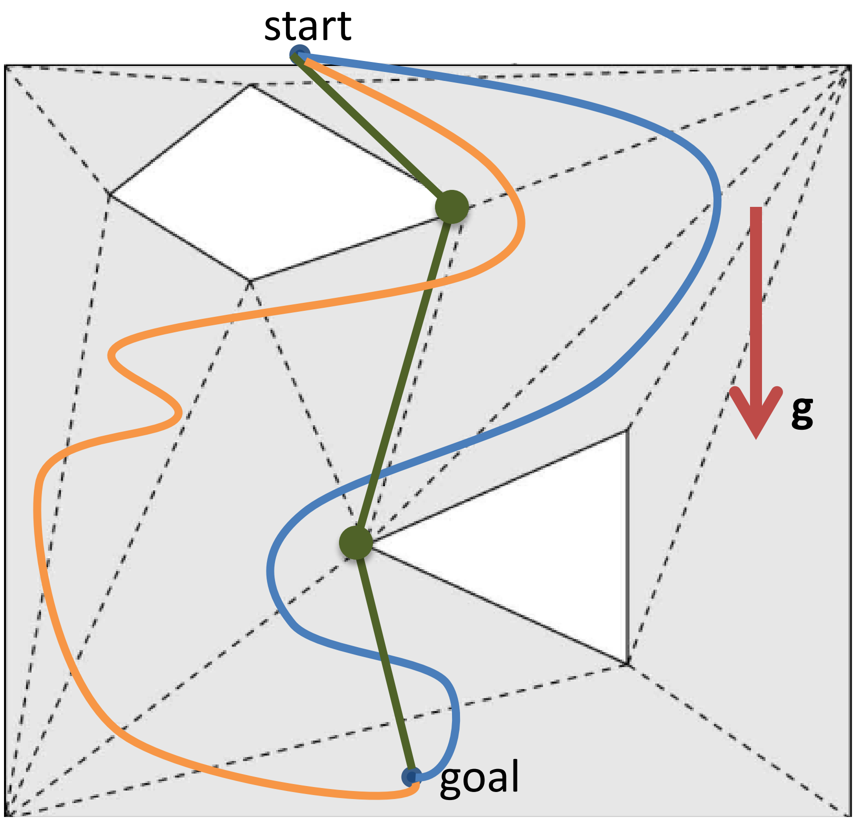
Ascent paths that are homotopic to the corresponding descent paths will avoid entanglement.

Given a feasible ascent path, we are interested in finding its **homotopy class**: the set of all curves *homotopic* to the ascent path.

Homotopy: It's what separates us from the animals

A Rough Guide to *Offline* Path Planning

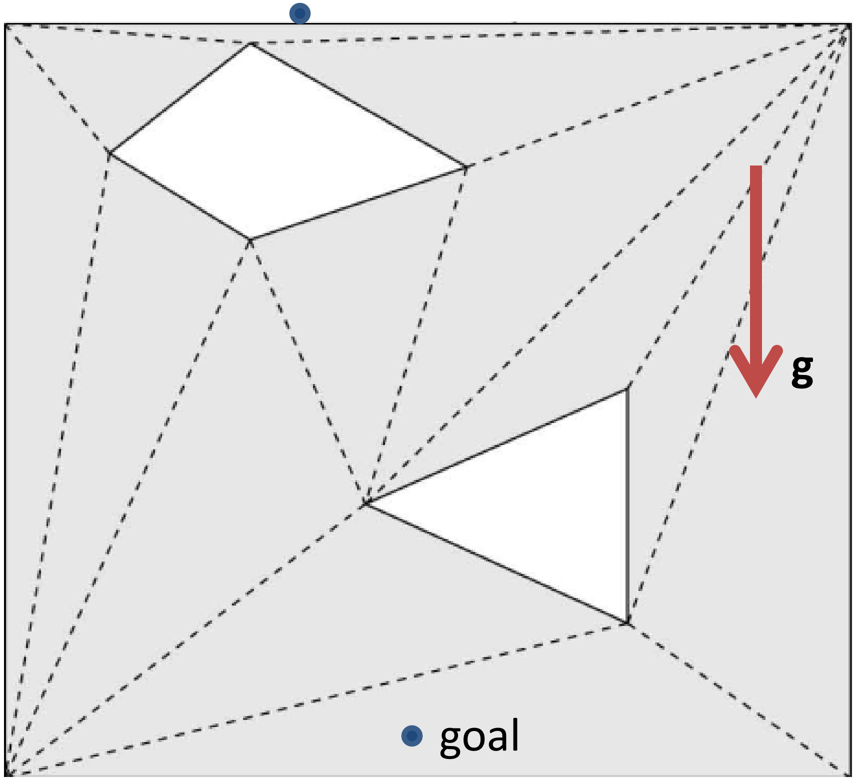
1) Triangulate
2) Find an ascent path
3) Check that ascent path is feasible using Shortest Homotopic Path (SHP) and anchor points
4) Find descent path that is homotopic to ascent path
5) Execute



Tether-demand plane

BTMs

- A Boundary Triangulated 2-Manifold (BTM) is a 2-dimensional simplicial complex in which all vertices are boundary vertices.
- A BTM for a given map is not unique.

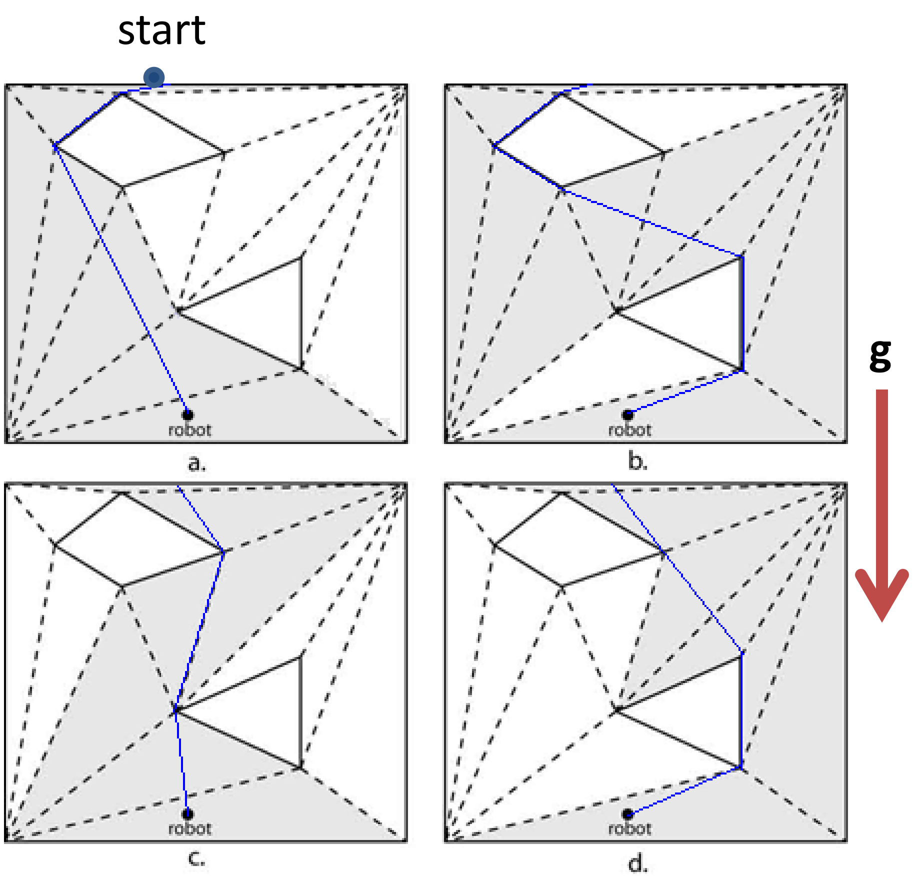


Tether-demand plane

[De Berg, 2000]

Shortest Homotopic Paths (SHPs)

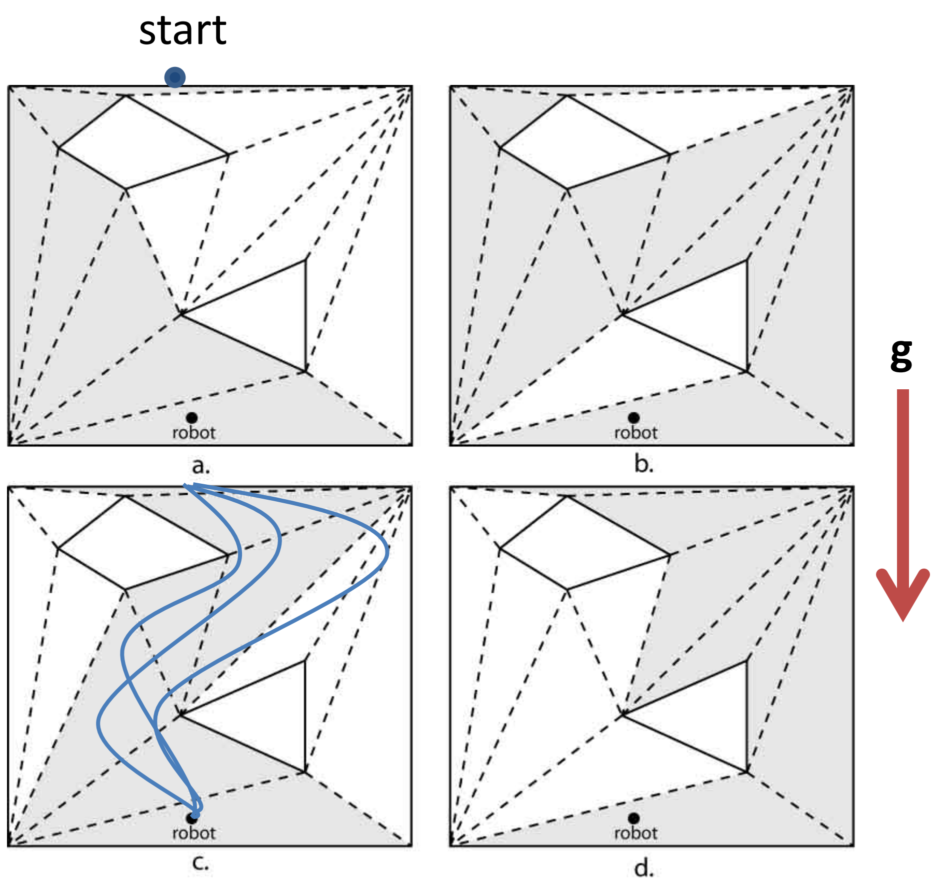
- The Shortest Homotopic Path (SHP) is the shortest path in a given homotopy class
- SHP = taut tether configuration
- Given a path, the sleeve can be found with the funnel algorithm, visibility graphs, or other methods



[Hershberger and Snoeyink, 1994], [Chazelle, 1982], [Lee and Preparata, 1984], [Bespamyatnikh, 2003]

Sleeves

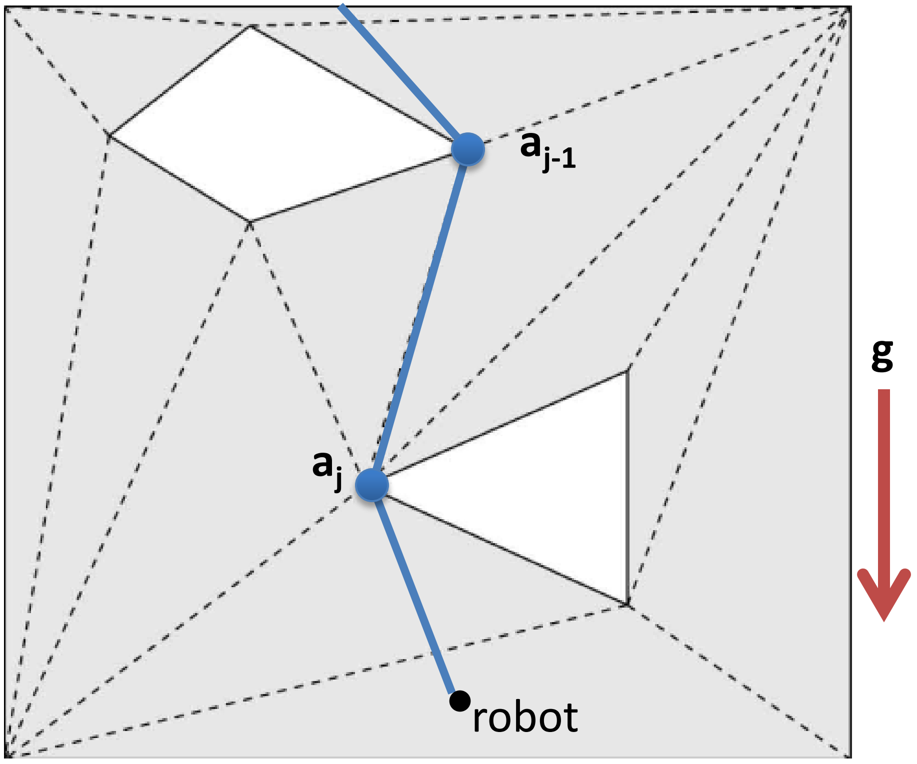
- A sleeve is a polygon formed by those BTM triangles through which a SHP passes.
- Any path entirely within the sleeve is homotopic to any other path within it.



[Hershberger and Snoeyink, 1994.]

Anchor Points

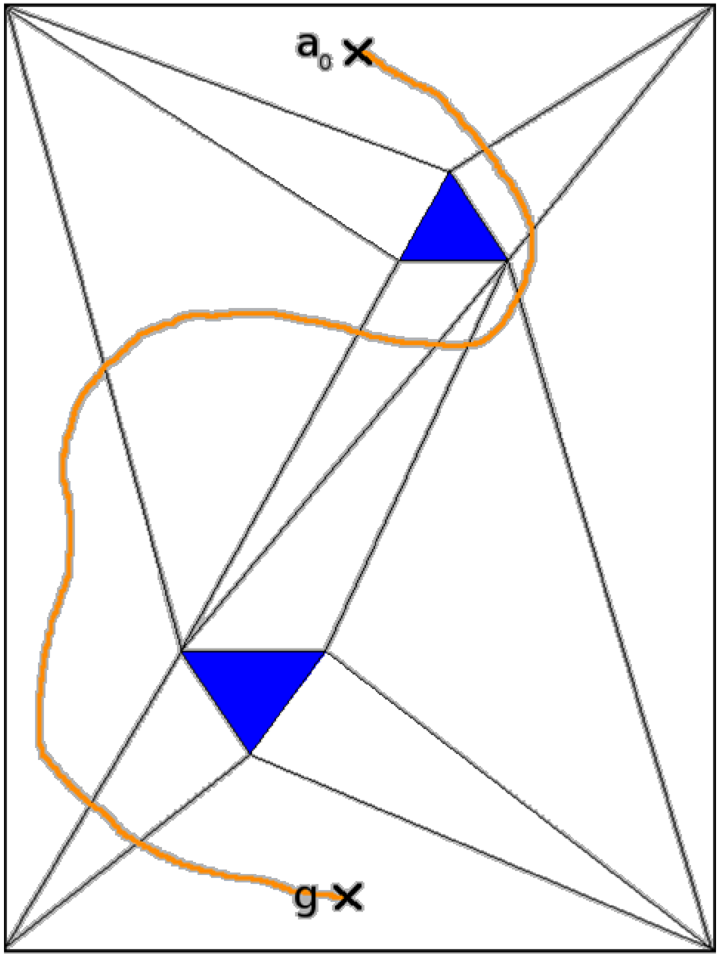
- **Anchor points** are where the taut tether contacts an obstacle
- An anchor point a_j is **passable** from a configuration q if the robot can reach a position that removes a_j from the SHP
- Reachability depends on terrain and robot's capability



[Abad-Manterola et al., 2011], [Abad-Manterola, 2012]

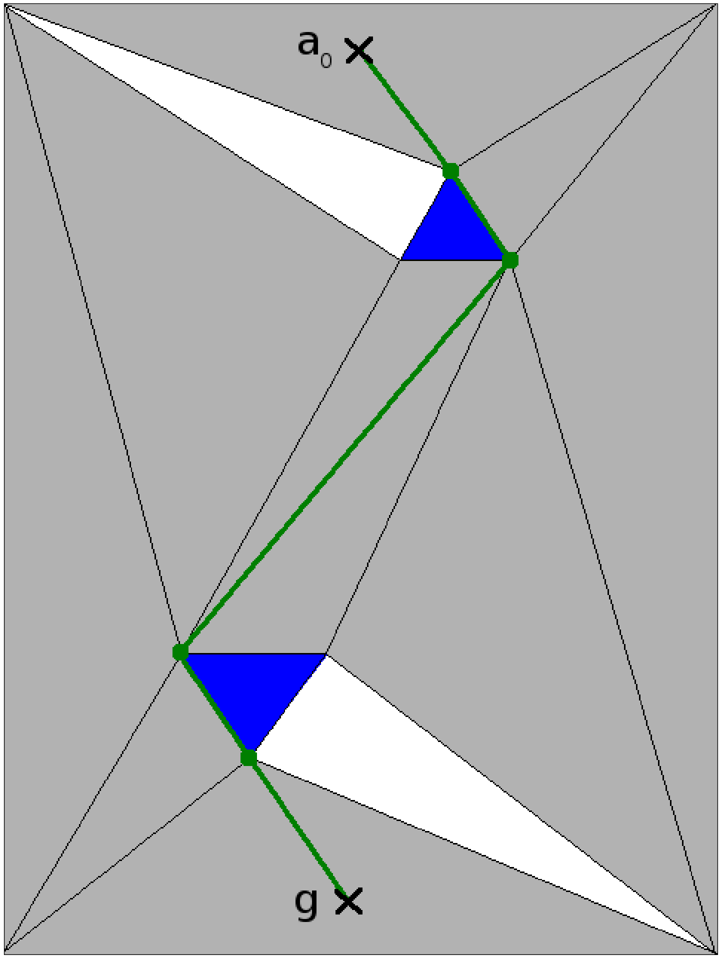
An Algorithm - Preplanning

- Map at right: start at a_0, end at g. Obstacles in blue.
- Triangulate to find the BTM
- Run a search algorithm to find a candidate path, shown in orange



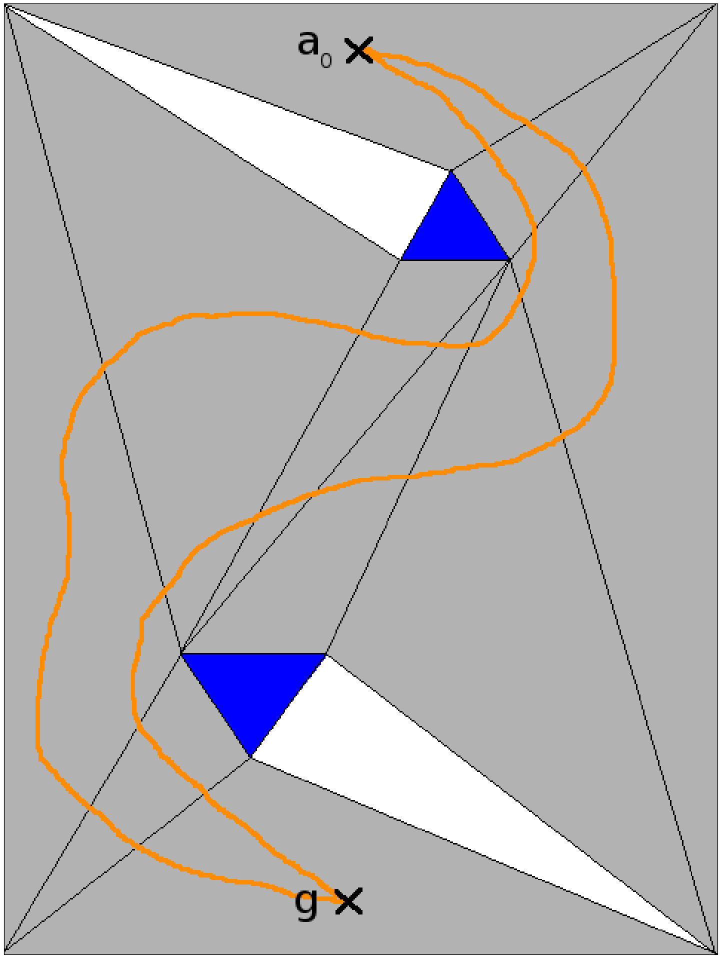
An Algorithm - Preplanning

- Find sleeve of candidate path, shown in grey
- Use funnel algorithm to find the SHP.
- Find anchor points, circled in green. Are they all passable? Use these to check SHP's feasibility.



An Algorithm - Preplanning

- If the SHP is feasible, select two paths in that sleeve (orange).
- If the SHP is not feasible, constrain the search to avoid this homotopy class. Continue looking until something is found (or timeout).



Tethered Motion Planning

Shackleton Crater Example

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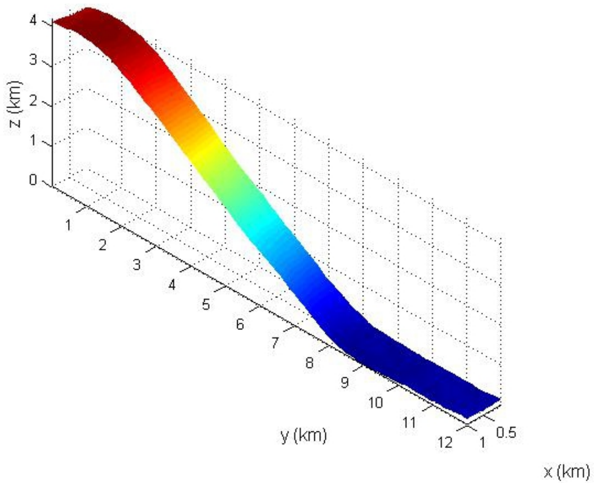
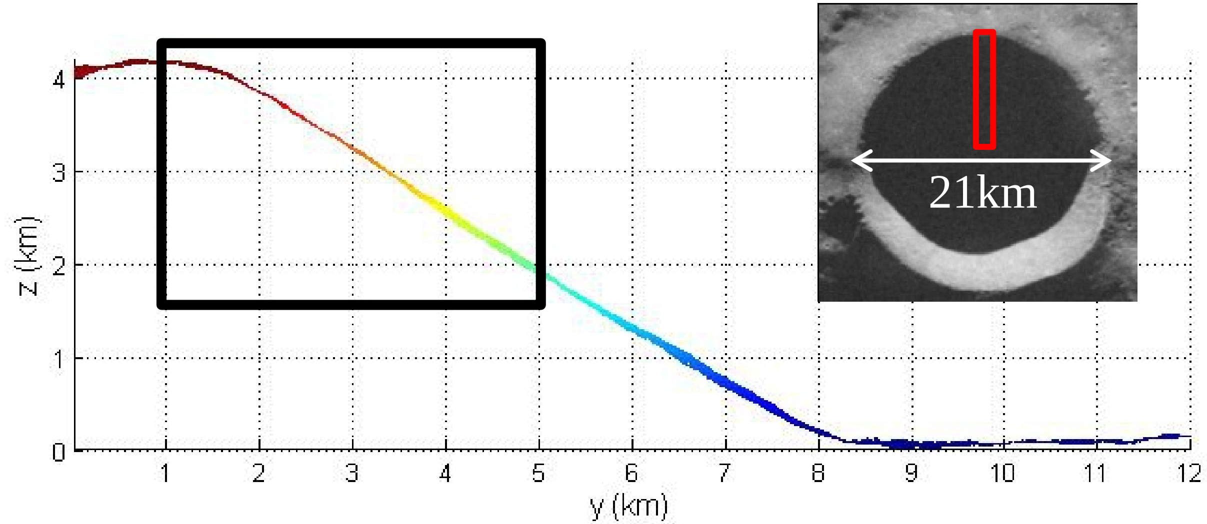
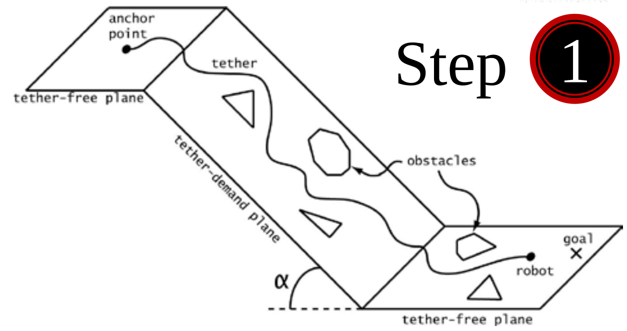




Data resolution
1 pixel = 1m x 1m in x-y plane
<10cm vertical resolution



Step 1 Model the terrain

Terrain Modeling
4km x 1km section divided into 4,000 planes, each 1m long x 1000m wide.

Slope Angle
α_i is the average slope of each plane, i = 1,…,4000.

Tethered Motion Planning

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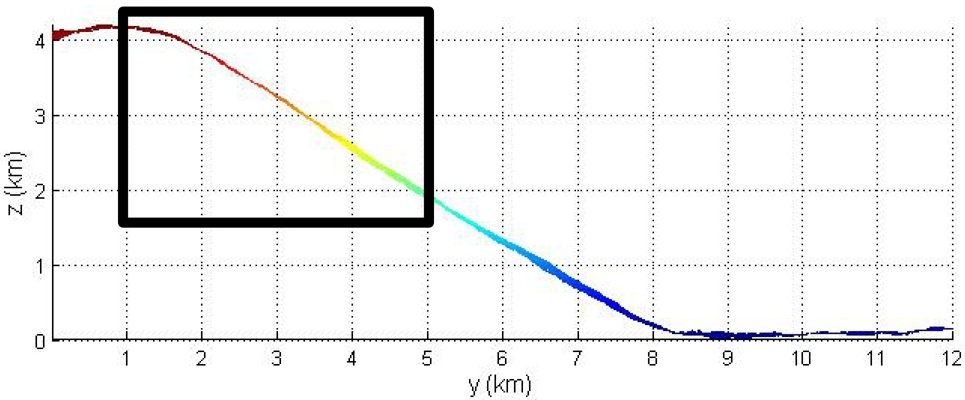
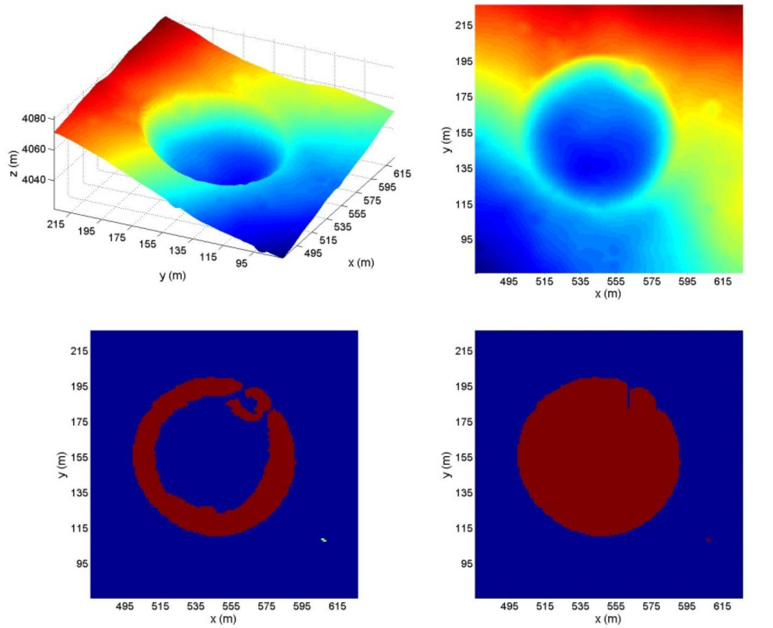
Step 1 Model the terrain

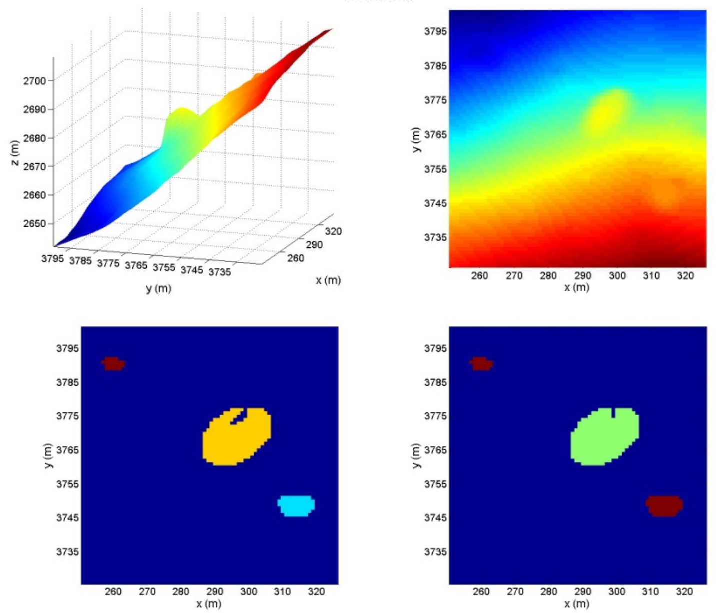


Detecting obstacles



Obstacle detected

Interior filled & classified (negative)



Obstacles detected

Interior filled & classified (2 negative & 1 positive)

Tethered Motion Planning

Shackleton Crater Example

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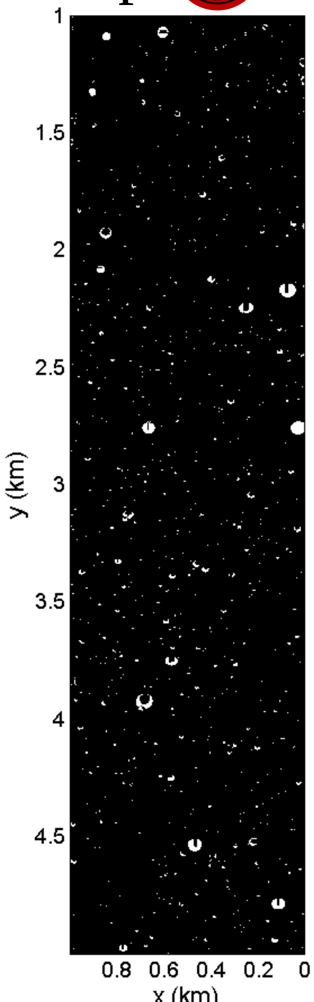
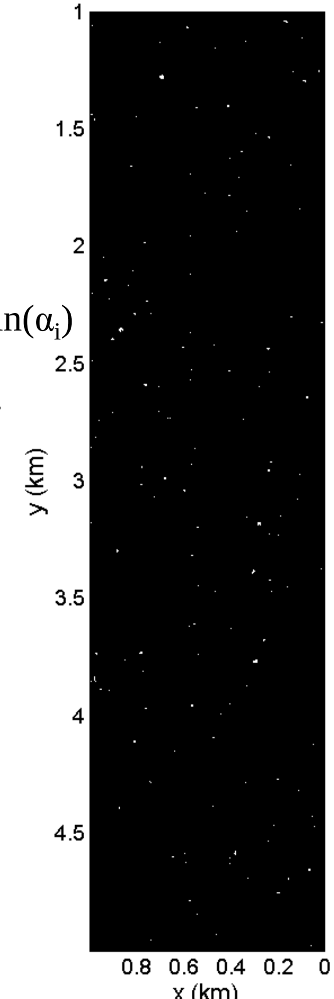
Step 1 Model the terrain

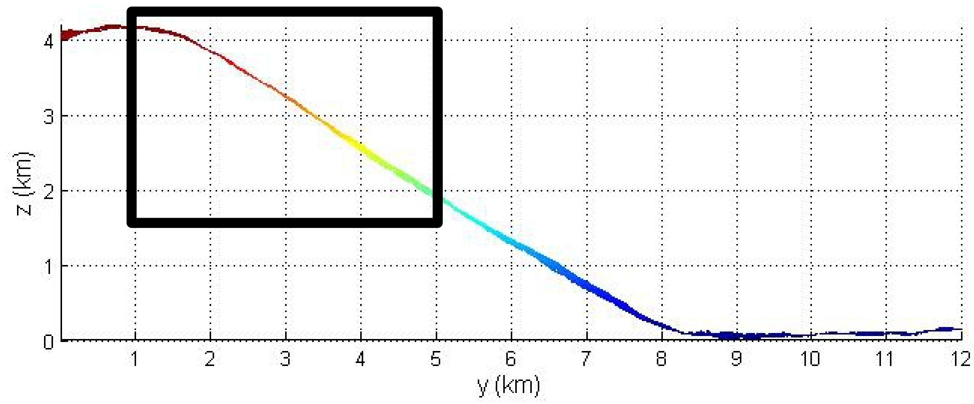


All Obstacles

$g \cdot \sin(\alpha_i)$



Positive Obstacles

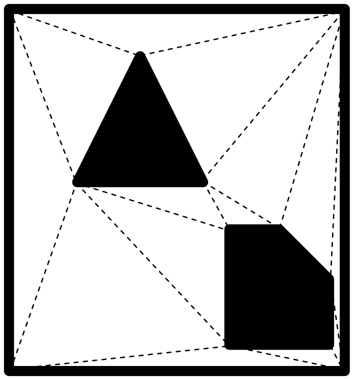


1,471 distinct obstacles detected

26% of obstacles are positive

Only positive obstacles determine the homotopy class of the rover's path in the triangulation.

Detecting obstacles

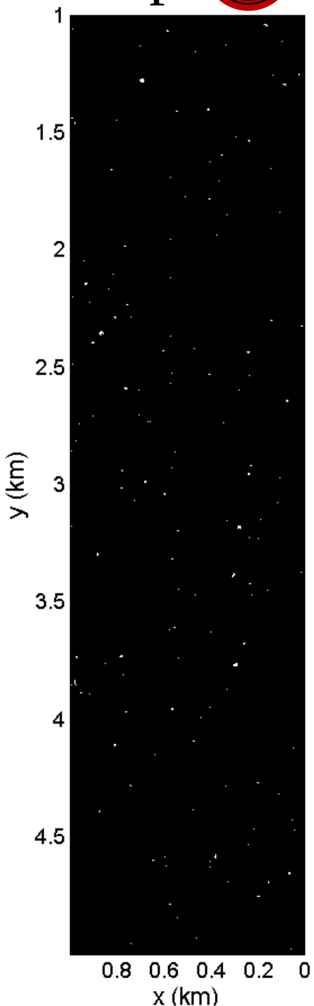


Tethered Motion Planning

Shackleton Crater Example

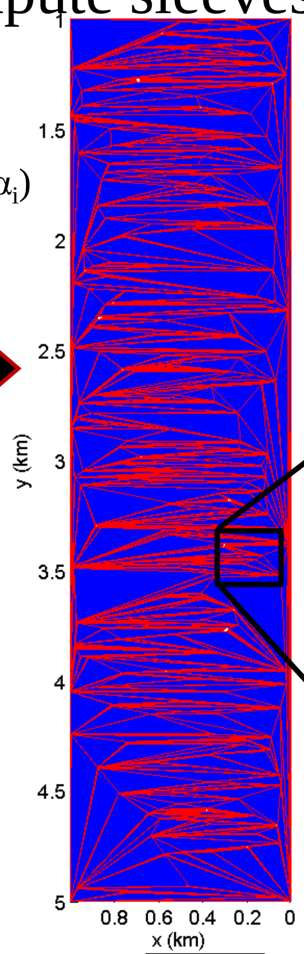
Jet Propulsion Laboratory
California Institute of Technology

Step 2 Construct BTM and compute sleeves

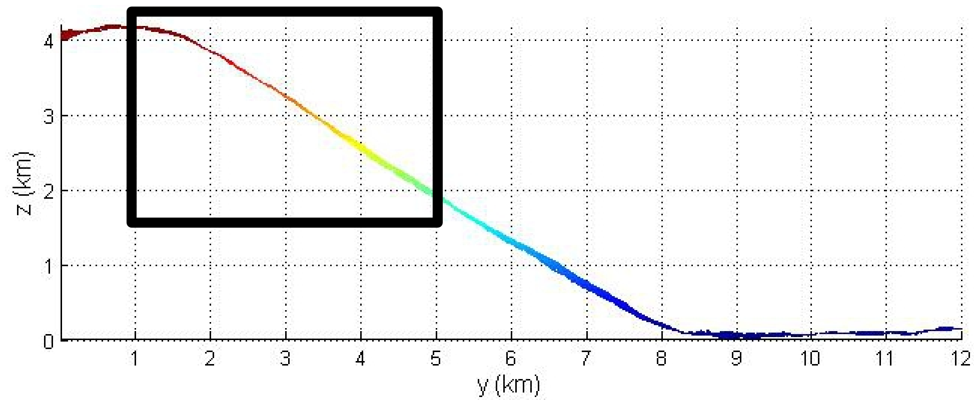


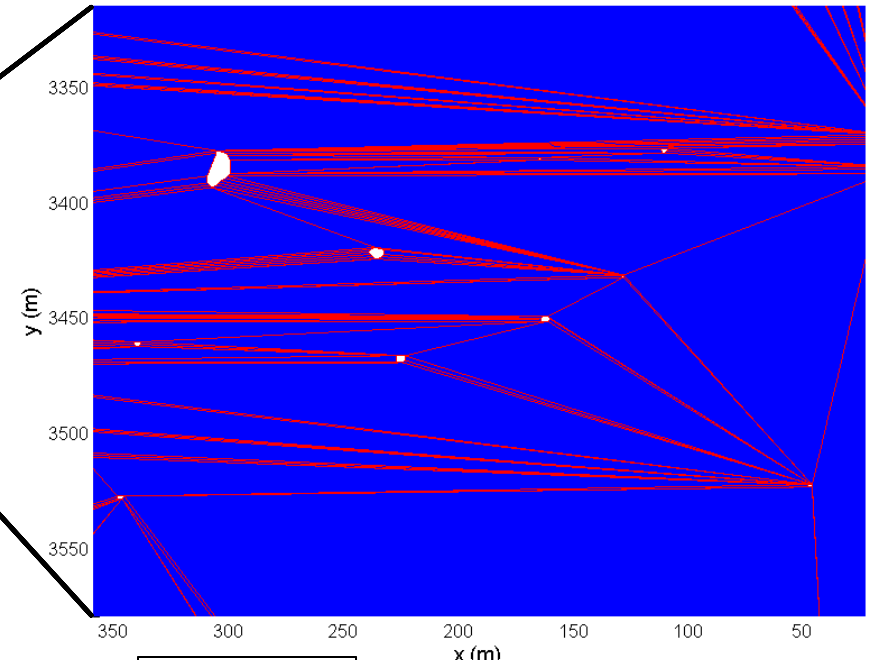
Positive Obstacles

$g \cdot \sin(\alpha_i)$



BTM



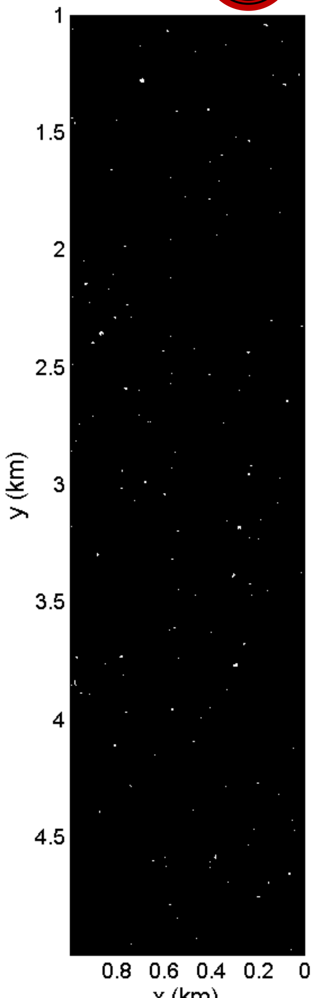


BTM detail

Tethered Motion Planning

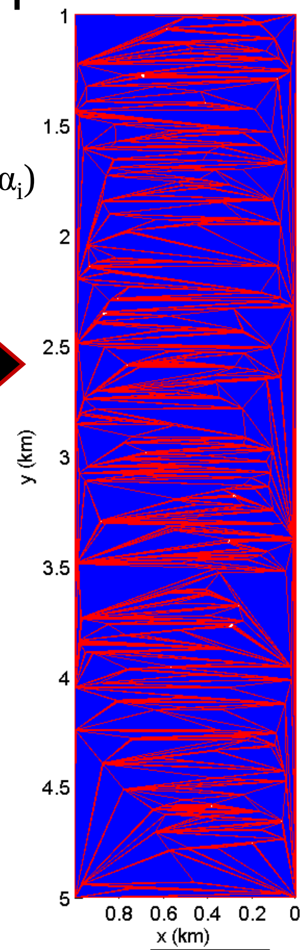
Shackleton Crater Example

Step 2 Construct BTM and compute sleeves

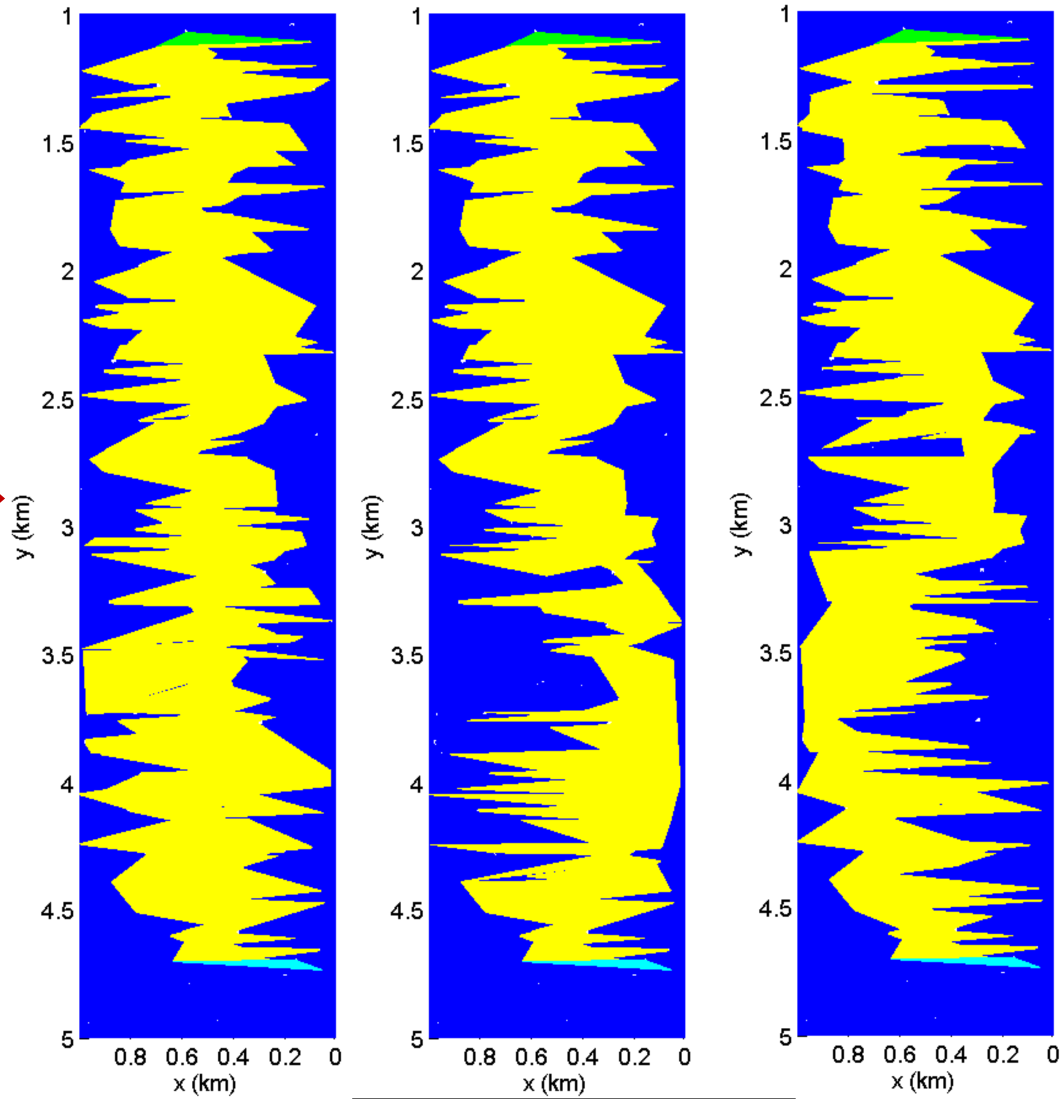


Positive Obstacles

$g \cdot \sin(\alpha_i)$



BTM



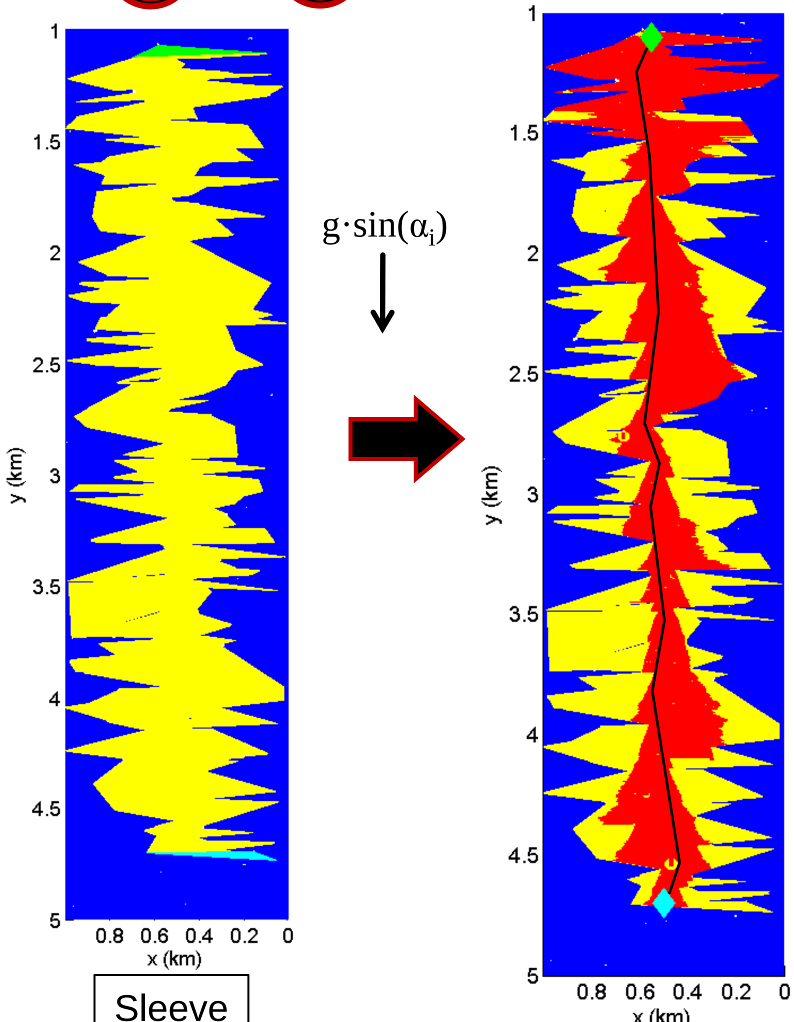
A few candidate sleeves

Tethered Motion Planning

Shackleton Crater Example

Jet Propulsion Laboratory
California Institute of Technology

Steps 3 & 4 Compute the SHP & Reachable Sets



Sleeve

Sleeve is discretized at every 1m x 1m pixel following the resolution of the data.

Reachable set is approximated by computing controllability at each individual point.

Controllability is based on the no-slip condition:

$$\left|\theta^{i}_{\max}\right| = \sin^{-1}\left(\mu \cot \alpha_i\right)$$

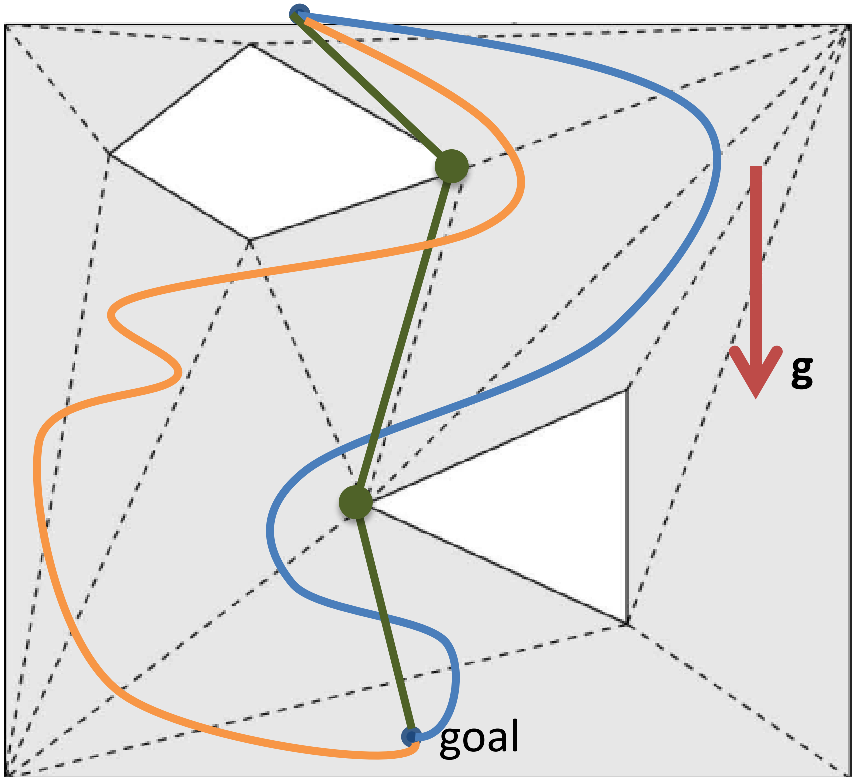
$$\mu_{moon} = .3$$

LEGEND

- anchor
- goal
- sleeve
- controllable subset of sleeve

A Rough Guide to *Online* Path Planning

1) Triangulate
2) Find an ascent path
3) Check that ascent path is feasible using Shortest Homotopic Path (SHP) and anchor points
4) Find descent path that is homotopic to ascent path
5) Travel designated descent path until map changes

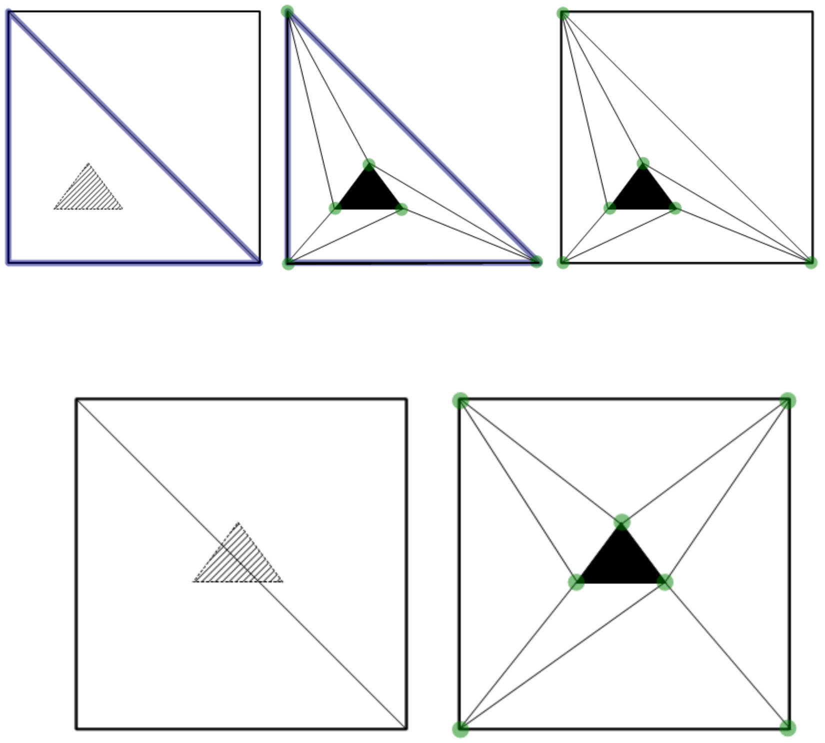


Tether-demand plane

[Tanner, Burdick, Nesnas ICRA13]

Retriangulating BTMs

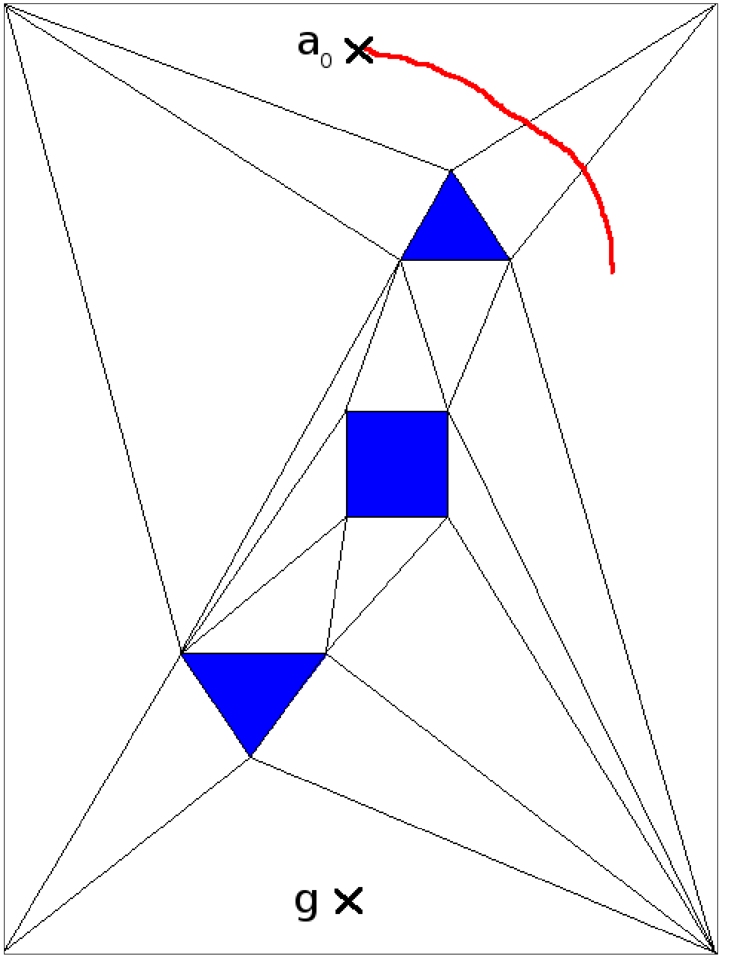
- How can we update the BTM?
- **Lemma 1**: Any BTM can be locally retriangulated in the affected region around a new or removed obstacle to construct a proper boundary triangulation which seamlessly meshes with the boundary triangulation outside the affected region. The resulting triangulation is a BTM.
- All changes can be made based on Lemma 1.



[Tanner, Burdick, Nesnas ICRA13]

An Algorithm - Retriangulating

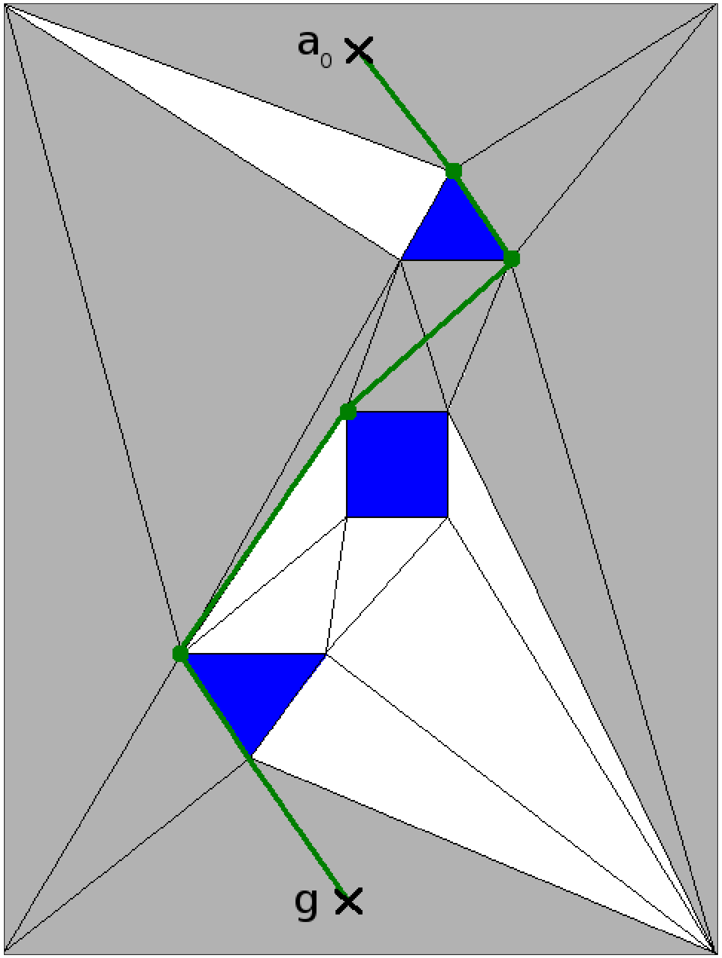
- Assume we've started down the previously planned path when a new obstacle is sighted.
- Retriangulate BTM.



[Tanner, Burdick, Nesnas ICRA13]

An Algorithm - Recomputing

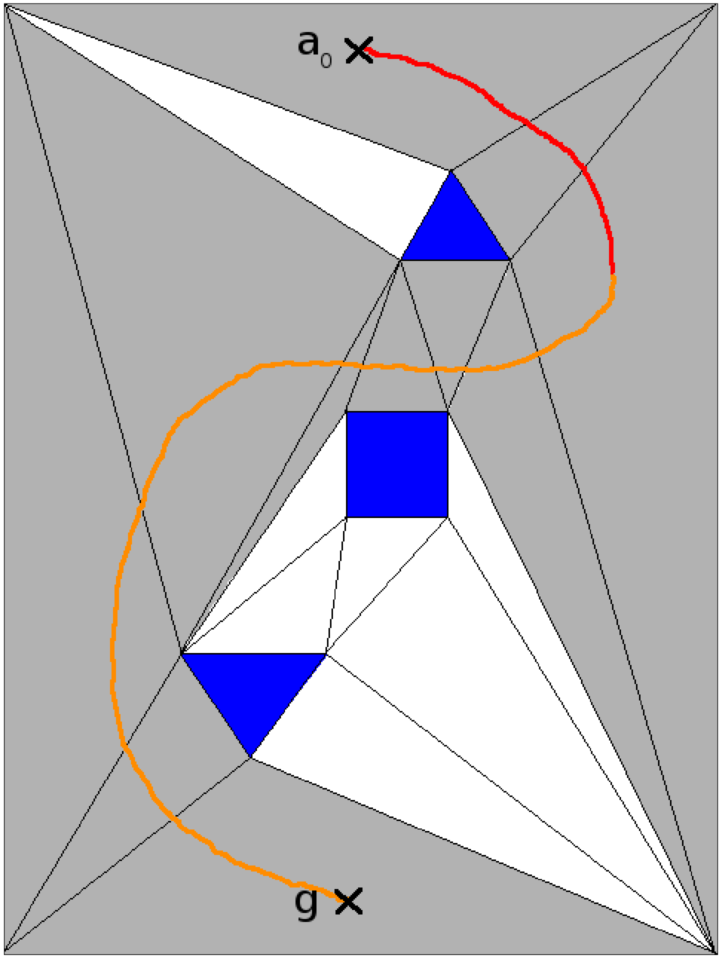
- Recompute sleeve, SHP, and anchor points (if change occurs in previous sleeve).
- Since anchor points have changed, rerun feasibility check on terrain.



[Tanner, Burdick, Nesnas ICRA13]

An Algorithm – Feasible Paths

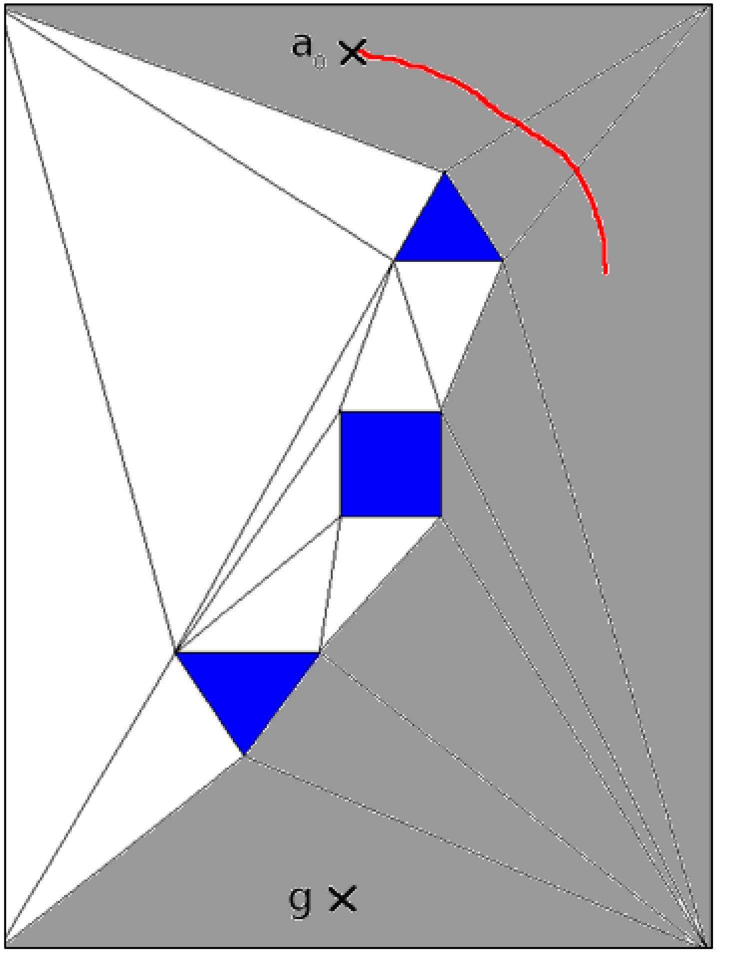
- If feasible path(s) exist
  - Select new descent path (orange)
  - Select new ascent path (not shown).
- If no feasible paths
  - Constrain search to avoid this sleeve
  - Backtrack until something feasible is found.



[Tanner, Burdick, Nesnas ICRA13]

An Algorithm- Backtracking

- Use complex analysis to constrain search, as in Bhattacharya et al., 2010.
- Search first in sleeves that share already-completed path section
- Then physically backtrack robot and search other sleeves
- Continue searching until success/all sleeves exhausted
  - Number of paths can be bounded, since we exclude multiple windings



[Tanner, Burdick, Nesnas ICRA13]

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CALIFORNIA INSTITUTE OF TECHNOLOGY 1891

JPL
Jet Propulsion Laboratory
California Institute of Technology

Keck
INSTITUTE FOR SPACE STUDIES

Personnel: Caltech

Graduate Students:

- **Melissa Tanner (3rd** year ME, started Dec. 1, 2011)
  - **Mechanical design:** DuAxel central module, Axel caster arm, sampling tools
  - **Thesis work:** will focus on automated planning for tether management
- **Krishna Shankar (1st** year ME, starting June 15, 2011)
  - Develop an *estimator* for Axel (fuse sensors to estimate Axel's attitude)
  - Automated map-making.

Undergraduate Students:

- **Sarah Ahmed (senior ME):** senior thesis on Axel Tension Sensor
- **2012 Summer SURF Students**
  - **Hima Hassenruck-Gudipati** (junior ME).
  - **Yifei Huang** (junior ME).
  - **Nikola Georgiev** (junior ME)
  - **Kristen Holtz** (junior ME)
  - **Diego Prabhakar** (junior ME)

KISS Student-Lead Project (Axel Sampling Tools)

Testing Obstacle Avoidance
Human in the Loop - Blind Drive

Axel Blind Drive – Observer View

Axel Blind Drive – Rover View
Ascending 35˚ Slope


Axel Blind Drive – Rover View
Ascending 35˚ Slope

Axel Blind Drive – Rover View Ascending 35° Slope

Axel Blind Drive – Rover View
Descending 35˚ Slope

Axel Blind Drive – Rover View
Descending 35˚ Slope


Axel Blind Drive – Rover View
Descending 35° Slope

Pose Estimation - Reprojections

- Typical pose reprojection error ~ 8 pix → 1 pixel/fiducial
- Sufficiently accurate, since error scales ~ with distance
  - 5m → Δ20cm
  - 2m → Δ8cm
  - 1m → Δ4cm