A Survey of Autonomous Navigation Techniques Applicable to Lunar Surface Exploration

Paul McKee

Aeroscience and Flight Mechanics Division
NASA Johnson Space Center

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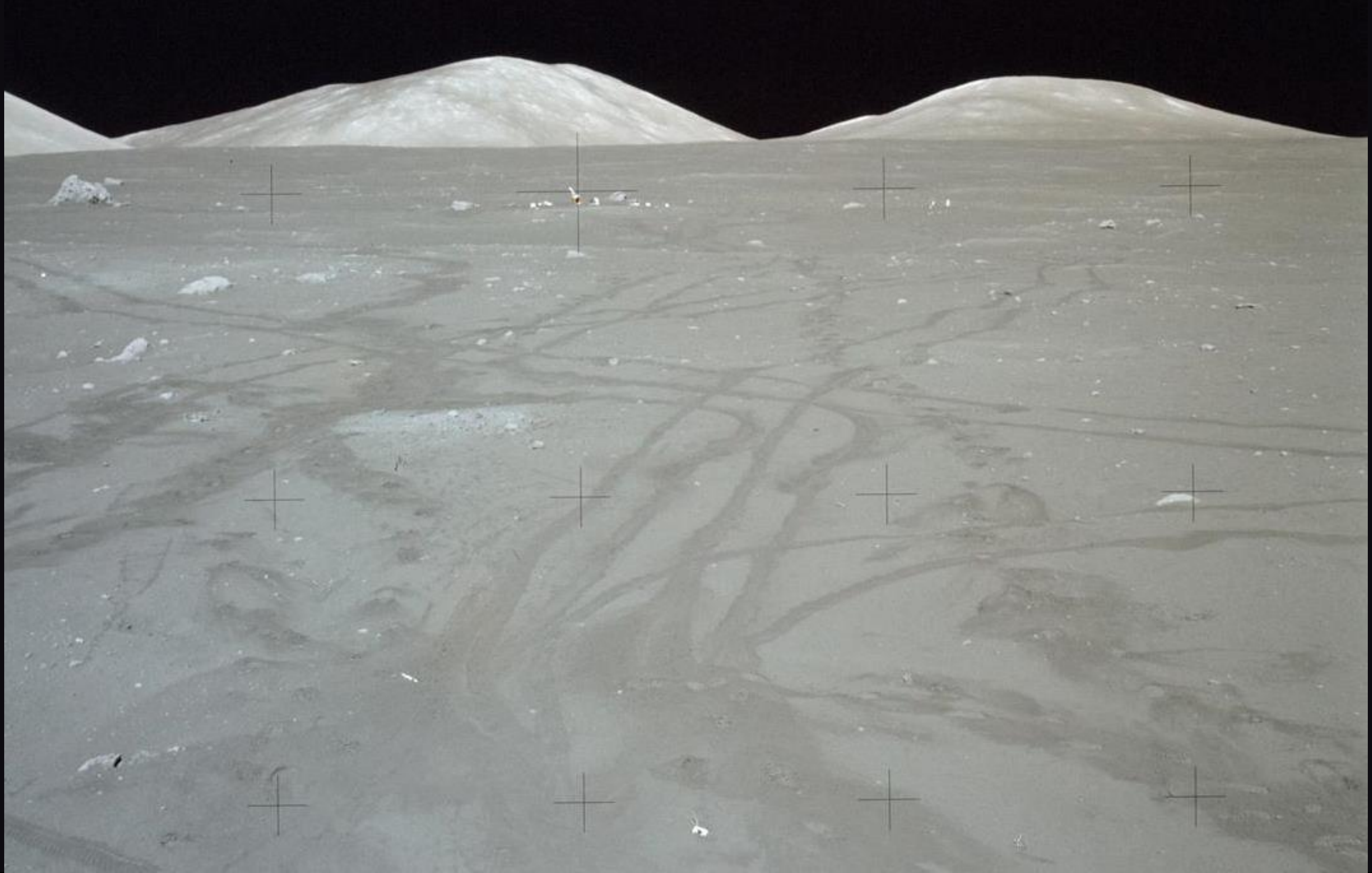
Which way back to the lander?

image credit: NASA

Good luck following tire tracks...



AS17-140-21355
image credit: NASA

What problems can we solve?

Assuming loss-of-communication scenario (no GPS, DSN, LCRNS)

Where am I with respect to some other asset? → local navigation

Am I going to hit something on the way to my destination? → hazard detection and avoidance (HDA)

What is my latitude/longitude? → global navigation

What sensors do we have?

- IMU
  - accelerometers → "felt" acceleration
  - gyroscopes → attitude rate
- Star tracker → star field image
- Wheel encoders → wheel revolutions
- Optical navigation cameras
  - mono camera → mono image
  - stereo camera pair → point cloud
  - point-able mast → panorama
- LIght Detection And Ranging (LIDAR) → point cloud

What do we do now?

• Didn't the Apollo people figure this out already?		Apollo LRV Case Study	slide 7,8
• What about the folks at JPL?		Mars Rover Case Study	slide 9,10
• What about the VIPER rover?		VIPER Case Study	slide 11
• Let's do a literature review…	local nav	Inertial Navigation/Dead Reckoning	slide 12
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Apollo LRV Case Study

- Lunar Roving Vehicle (a.k.a. "Moon Buggy")
- "An intricate navigation system is not needed, nor is there time to develop one" – Bill Tindall
- Local navigation → inertial navigation and wheel odometry
- Hazard detection → crew eyeballs
- Global navigation → orienteering (crew eyeballs + map)

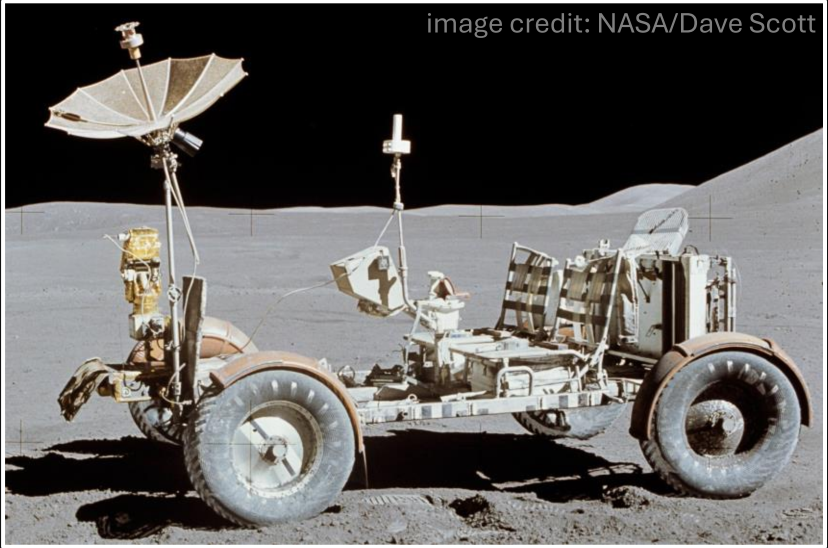


image credit: NASA/Dave Scott

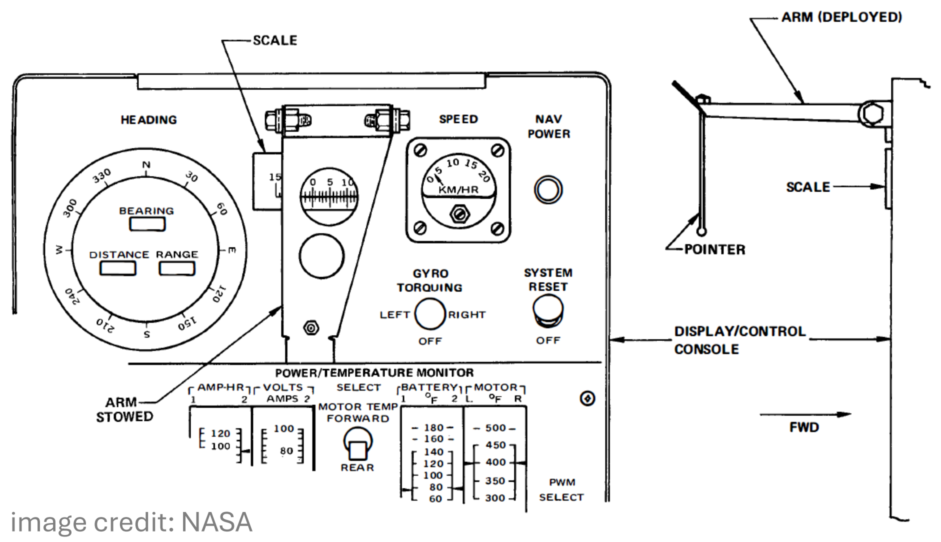


image credit: NASA

Apollo LRV Case Study: Considerations

- Orienteering fell short on Apollo 14
  - crew became disoriented and “admitted defeat” 30 meters from target

- Cannot rely on direct line-of-sight to a tall lander
  - terrain obscures lander, must be able to navigate to within 1km

- Lunar surface plays tricks on the human eye
  - terrain self-similarity
  - extreme lighting conditions
  - no sense of scale

Mars Rover Case Study

- Mars Pathfinder – Sojourner (1997)
  - local navigation → inertial navigation and wheel odometry
    → images taken by Pathfinder lander
  - hazard detection → stereo camera pair, laser striper, contact sensors
  - global navigation → N/A

- Mars Exploration Rover – Spirit & Opportunity (2004)
  - local navigation → inertial navigation and wheel odometry
    → images of the Sun to update gyros
    → *visual odometry (demonstration)*
  - hazard detection → stereo images processed into hazard map
  - global navigation → human-in-the-loop orbital image comparison

image credit: NASA/JPL

Mars Rover Case Study

- Mars Science Laboratory – Curiosity (2012)
  - local navigation → inertial navigation and wheel odometry
    → images of the Sun to update gyros
    → *visual odometry (now standard)*
  - hazard detection → stereo images processed into hazard map
  - global navigation → human-in-the-loop orbital image comparison

- Mars 2020 – Perseverance (2021)
  - local navigation → (see Curiosity)
  - hazard detection → on-board hazard map generation at full drive speed
  - global navigation → human-in-the-loop orbital image comparison

- Mars 2020 – Ingenuity (2021)
  - local navigation → inertial navigation, laser altimeter, visual odometry
  - hazard detection → human operators plan a safe flight path
  - global navigation → N/A

image credit: NASA/JPL

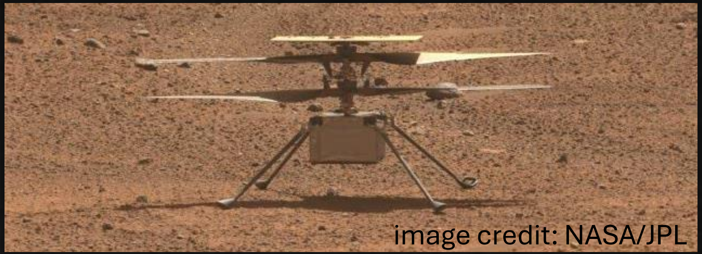


image credit: NASA/JPL

VIPER Case Study

- Volatiles Investigating Polar Exploration Rover
- “cancelled” in July 2024 (work continues at NASA Ames and Johnson Space Center)
- Local navigation → inertial navigation and wheel odometry
  → star tracker to update gyro
  → visual odometry
- Hazard detection → hazard cameras (HazCam) in wheel wells (4)
  → stereo pair of navigation cameras (NavCam) on mast
  → stereo pair of aft-facing cameras (AftCam) on body
- Global navigation → human-in-the-loop orbital image comparison

image credit: NASA

- VIPER does not need the autonomy of the Mars rovers due to its proximity to Earth

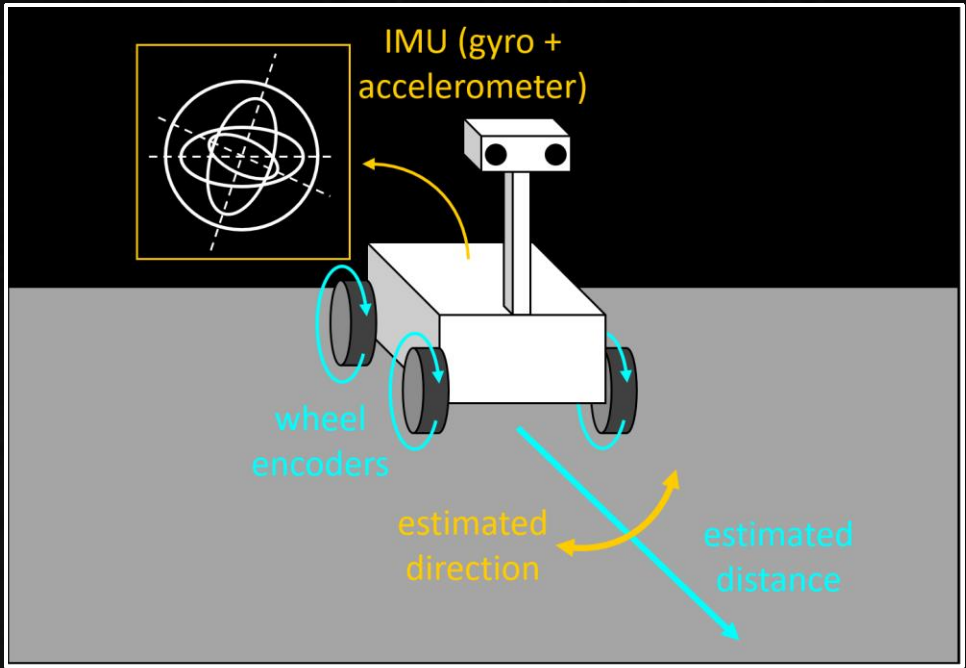
Inertial Navigation and Wheel Odometry

- count wheel revolutions to determine distance traveled
- integrate rate gyros to determine direction traveled

- must account for gyro drift (external measurements)
- must account for wheel slip (various solutions)

- *flown on every rover to date*

Navigation Type	local
Hardware	• wheel odometers (or equivalent) • IMU • suspension encoders (optional)
Considerations	• wheel slip • gyro drift

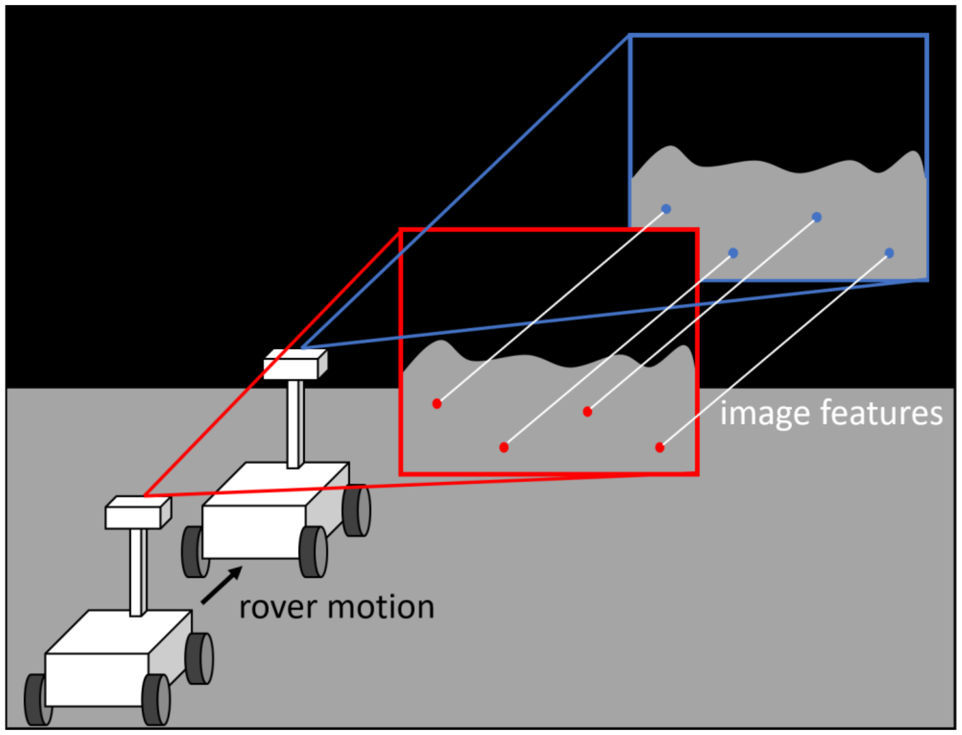


Visual Odometry

- take "before" image, drive a bit, take "after" image
- process both, looking at image features (SIFT, SURF, ORB, KAZE, etc.)
- correlate features between images (often requires RANSAC or similar)
- points (should be) truly static
- compute change in observer pose (pos+att)

- can be on-board or post-processing

Navigation Type	local
Hardware	• stereo camera pair OR • mono camera with range sensor • FPGA or GPU (optional)
Considerations	• choice of feature points • point correspondence problem



Simultaneous Localization and Mapping

- extension of visual odometry
- can be done with or without IMU (image only is “VSLAM”)
- estimate observer pose and location of (many) landmarks
- map generated upon loop closure
- related to Structure From Motion (SFM)
- can be on-board or post-processing

Navigation Type	local
Hardware	• mono/stereo cameras or LIDAR • IMU (opt.), FPGA or GPU (opt.)
Considerations	• (those of visual odometry) • requires loop closure • computer storage limitations • *no space flight heritage*

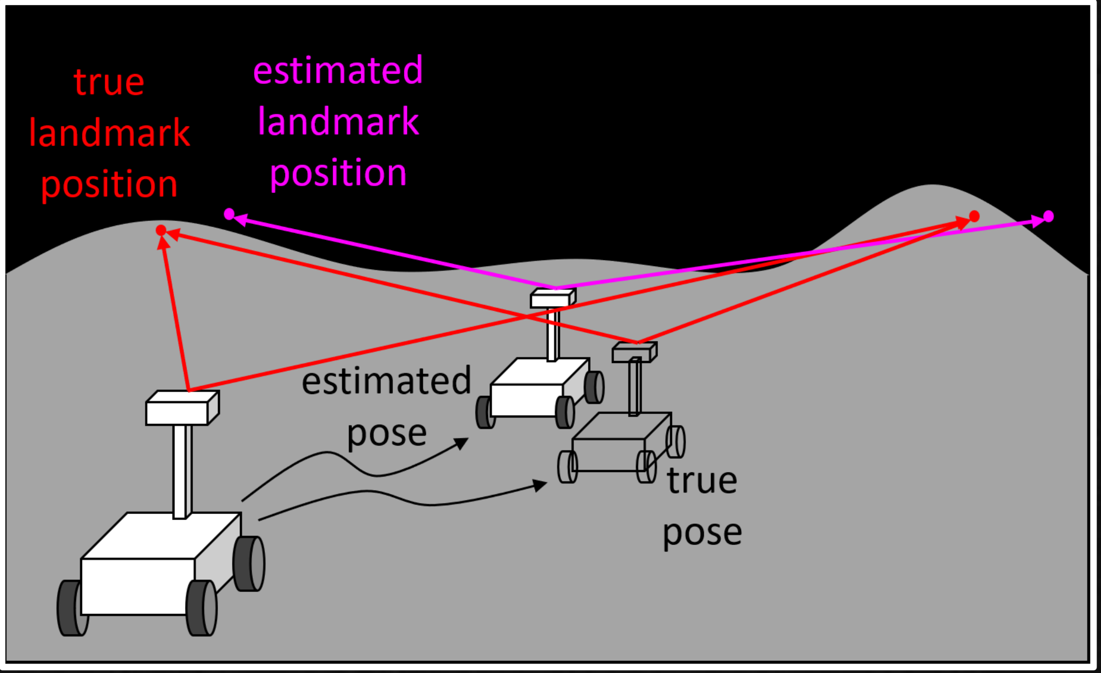
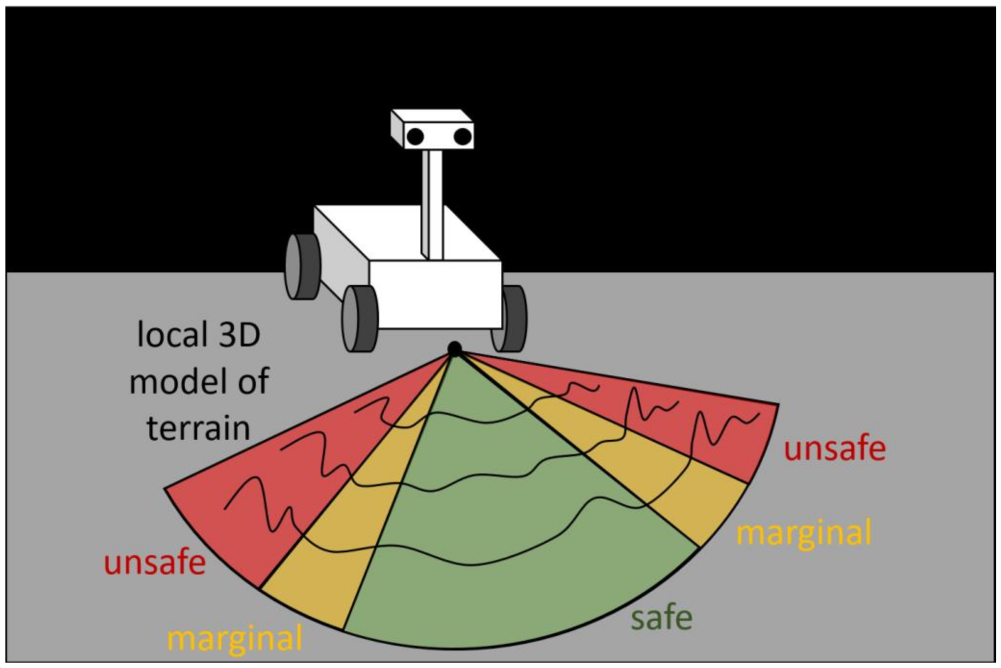


Image-Based Path Planning

- measure or generate 3D model (point cloud) of local terrain
- fit rover shape model to point cloud
- determine safe and unsafe regions ahead of rover
- rinse and repeat

- more complex rover shape model → "braver" path
- standard on Mars rovers

Navigation Type	hazard detection and avoidance
Hardware	• stereo camera pair or LIDAR • IMU • FPGA or GPU (opt.)
Considerations	• computationally expensive • necessary throughout traverse

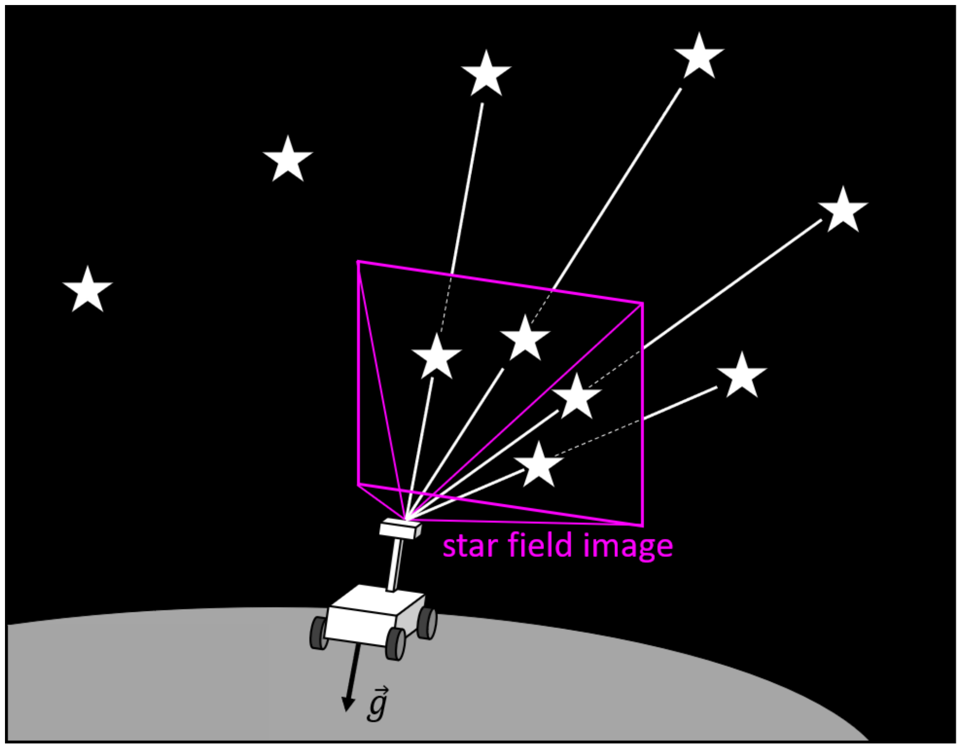


Celestial Navigation

- measure local gravity vector in vehicle frame (IMU)
- take star field image, determine vehicle's inertial attitude
- crunch numbers, find local "down" direction in Moon frame
- local down points (roughly) opposite position
- compute latitude and longitude

- must account for non-spherical gravity field
- must calibrate IMU-star tracker interlock angle

Navigation Type	global
Hardware	• star tracker, IMU, clock
Considerations	• must know (and re-calibrate) IMU-star tracker alignment • *no space flight heritage*

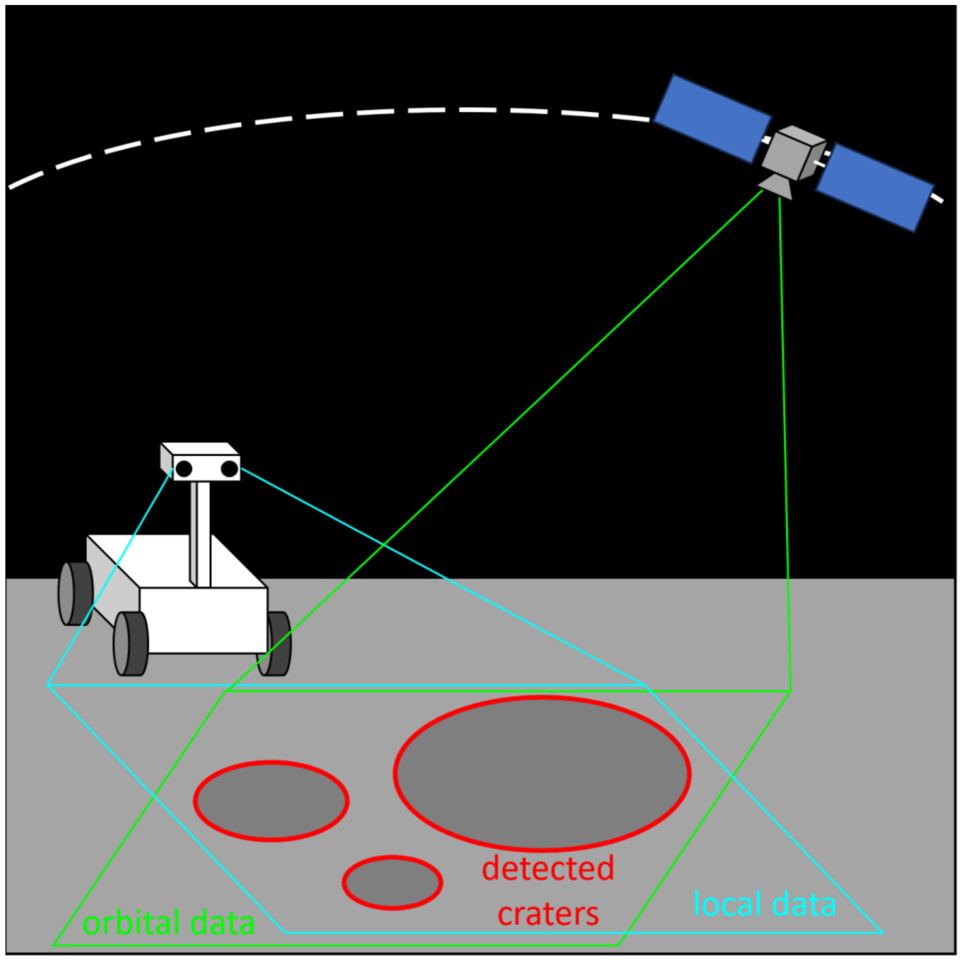


Surface Crater Navigation

- take image(s) or generate 3D model of local terrain
- detect craters (no small feat)
- generate crater map from orbital images
- compare detected craters to map (ad hoc)

- much more well-studied for orbital applications
- can be on-board or post-processing

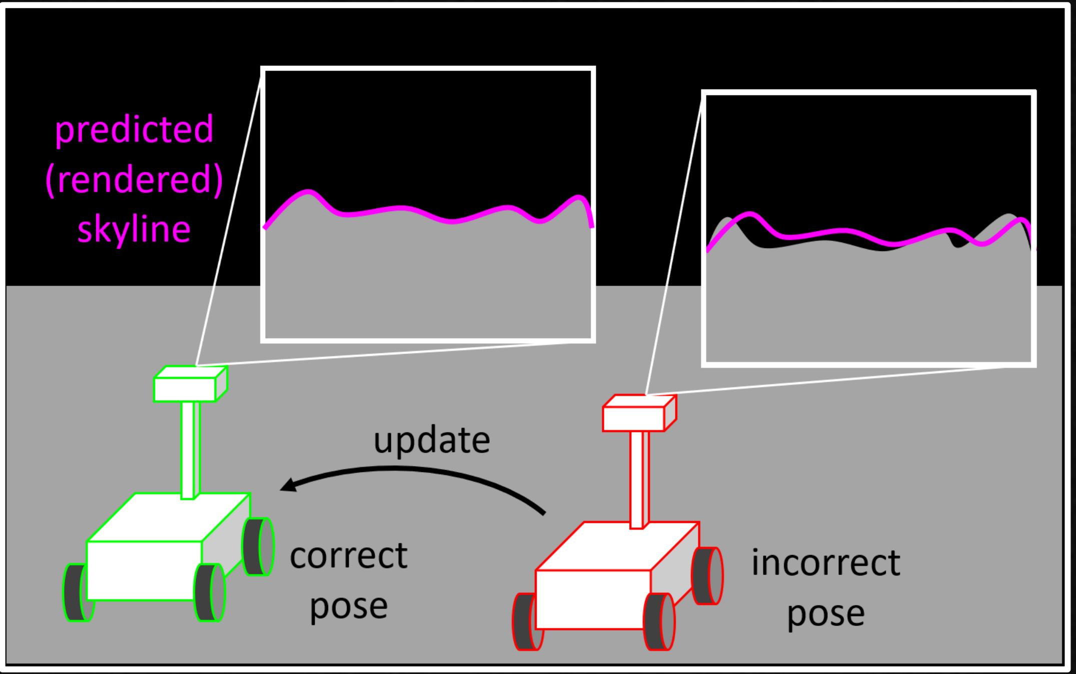
Navigation Type	global
Hardware	• mono/stereo cameras or LIDAR • FPGA or GPU (optional)
Considerations	• surface crater detection → CDA • surface crater ID problem • needs dense crater distribution • *no space flight heritage*



Skyline Navigation

- take image(s) of horizon, ideally construct panorama
- process to find horizon points, convert pixels → az,el angles
- coarse comparison
  - pre-render skylines at several points before launch
  - compare observed skyline to catalog, return best position
- fine comparison
  - iteratively re-render skyline and update pose estimate
- can be on-board or post-processing

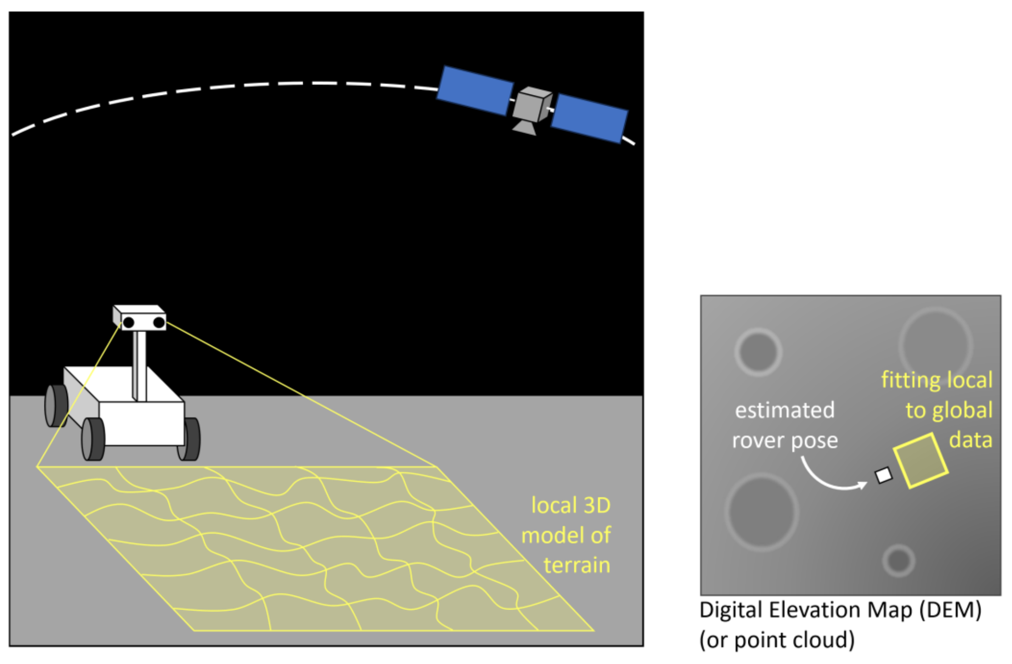
Navigation Type	global
Hardware	• mono camera or stereo cameras • FPGA or GPU (optional)
Considerations	• must render skylines (on board or before mission) • point correspondence problem • *no space flight heritage*



DEM Correlation

- measure or generate 3D model (point cloud) of local terrain
- generate point cloud of terrain from (orbital) DEM data
- compare local to global shape model using 3D features
  - see SHERIF project, stitching LIDAR scans
  - 3D equivalent of 2D image features (e.g., SIFT, SURF, ORB, KAZE)
- estimate observer pose
- can be on-board or post-processing

Navigation Type	global
Hardware	• stereo camera pair or LIDAR • FPGA or GPU (optional)
Considerations	• 3D feature correspondence • *no space flight heritage*

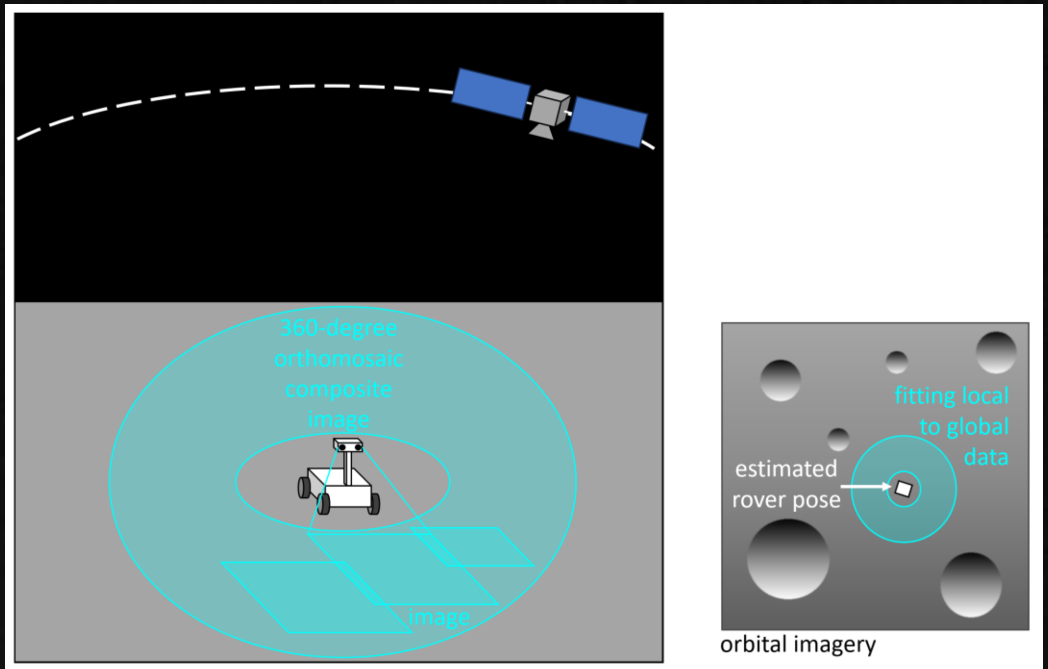


Digital Elevation Map (DEM) (or point cloud)

Orbital Image Correlation

- take several stereo image pairs (enough to make panorama)
- construct orthomosaic image
  - need depth and brightness info for each pixel
- compare to orbital image of mission region
  - bound search area with initial position estimate
- the “Censible” algorithm does this
  - modified census transform for image comparison
  - demonstrated on Perseverance rover
- can be on-board or post-processing

Navigation Type	global
Hardware	• stereo camera pair + mast • FPGA or GPU (optional)
Considerations	• computationally expensive • *minimal space flight heritage*



We have options!