Where to find these slides?
josh.vanderhook.info
publications/
after 4/21/22
What does our group/section do?
(shamelessly borrowed)

ai.jpl.nasa.gov
Go watch this brief overview by astrobiologist Kevin Hand

Credit: IFE, URI-IAO, UW, Lost City Science Party; NOAA/OAR/OER; The Lost City 2005 Expedition
Autonomous Science

Hydrothermal Venting

- Detecting and tracking of scientific features of interest
- Requires encoding of expert knowledge of scientific phenomena into autonomous algorithms
- Hydrothermal Venting is one such phenomena of interest
  - Harbors unique ecosystem based on chemosynthesis
  - Potential for hydrothermal venting on Europa. Evidence for venting on Enceladus
  - Sensors: Temperature, Oxidation Reduction Potential, Optical Backscatter

Credit: IFE, URI-IAO, UW, Lost City Science Party; NOAA/OAR/OER; The Lost City 2005 Expedition
Ocean Worlds Submersible Concept Mission

- Long duration mission
  - 1+ years to penetrate ice plus 1 year mission underwater
  - Travel 100’s of km from base station
- 3 main components: Surface antenna, under-ice base station, submersible
- Limited communication windows due to orbital occlusions (~42.5 and ~33 hours per orbital period of Europa and Enceladus respectively). No communication when distant from base station, sometimes 100s of km
- Dynamic environment prevents traditional human in the loop operations (e.g. Mars Rovers)
- Due to environmental and communication constraints, full autonomy is needed for weeks or months at a time.

Predecisional, for planning and discussion only
Onboard Autonomy Requirements for an Ocean Worlds Submersible Mission

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⁵Applied Physics Laboratory, University of Washington

- Performed 5 runs over 4 days, successfully located simulated hydrothermal venting.

- Full Simulation Success Rate
  - Nested Search: 80%
  - Greedy Transect: 56%
  - Gradient Ascent: 4%
  - Higher success rates correlate with longer search times

Autonomy architecture, showing the main components required for automated nested search using the Iver2 AUV

Iver2 AUV parked on the shore at NRL’s Chesapeake Beach Detachment after performing an experiment

Image Credit: C. German, WHOI

Deployment Results with Simulated Data
The targeted concentration of the neutrally buoyant tracer, starting location, and vent source are plotted.
To be confident in our predictions, we must measure the critical points to establish ground truth

https://www.youtube.com/watch?v=x1SgmFa0r04
Science planning for Orbiting Carbon Observatory-3

Sensitive spectrometers can measure the rate of environmental absorption of CO2

https://www.youtube.com/watch?v=7GMjU5pSufk
Automated instrument pointing from science plans

Challenging constraint satisfaction problem
A volcanologist called a colleague at JPL, asking if they could get photos of a volcano that just started erupting, and the spacecraft had already recognized that need and sent the images back the night before (EO-1).

You’ll love this one…

Figure 4. Sensorweb Detection and Response Architecture
Mars Rovers

ai.jpl.nasa.gov
Check out the landing video:
https://www.youtube.com/watch?v=4czjS9h4Fpg

Disclaimer: We did not contribute to EDL / Skycrane directly.
Self-driving rover (sort of)

The 2022 NASA Mars Rover was released (from its atmospheric descent cowl) yesterday. It's a limited edition of one.

Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.

Electric Drivetrain

Six electric motors, one per wheel, drive Perseverance. Power comes from a 99-pound radioisotope thermoelectric power generator using 11 pounds of plutonium-238 oxide, making refueling deadly and hopeless.

The suspension is a complex unit NASA calls a “rocker-bogie” design. It works to maintain a relatively constant weight on each of the six wheels as it moves over uneven terrain. Four-wheel steering is standard, as the front and rear wheels can each rotate 360 degrees.

Available only in 6-wheel drive, the rover boasts a top speed of 0.09 mph, good for a new world speed record (think about it). It boasts a 0-to-60 time of nope.

Handling is a bit sluggish, as drivers must send commands from Earth and wait approximately 20 minutes for them to reach the rover on Mars before they can be carried out. However, new self-driving software should allow the rover to make more independent decisions about how to cross obstacles in its path, reducing the need for direct inputs from an earthbound driver.

Lightweight aluminum wheels are standard and strengthened for off-road performance on a planet with no roads. “Engineers redesigned the Mars 2020 Perseverance rover’s wheels to be more robust due to the wear and tear the Curiosity rover wheels endured while driving over sharp, pointy rocks,” NASA explains. “Perseverance’s wheels are narrower than Curiosity's, but bigger in diameter and made of thicker aluminum.”
- Manual path planning is limited within the line of sight
- Up/down link: once per Sol (Martian day = 24hr40min)
- AutoNav extends drive distance per Sol beyond the line of sight
- AutoNav successfully drove on MER/MSL rovers
Directed driving

“Just wheel speeds”

Visual odometry, or Slip Check + “Auto”

“+check for slip”

Auto-navigation; Geometric Hazard Detection and Avoidance

“Self driving and mapping”
Driving Curiosity: Mars Rover Mobility Trends During the First Seven Years

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- Autonav is historically rare
- VO is really the only way to detect wheel slip or nav errors
- Yet still carries a 0.1-1.0% drift rate
Why 1% growth?

\[
\hat{x}_{k|k-1} = f(\hat{x}_{k-1|k-1}, u_k)
\]
\[
P_{k|k-1} = F_k P_{k-1|k-1} F_k^T + Q_k
\]
\[
\tilde{y}_k = z_k - h(\hat{x}_{k|k-1})
\]
\[
S_k = H_k P_{k|k-1} H_k^T + R_k
\]
\[
K_k = P_{k|k-1} H_k^T S_k^{-1}
\]
\[
\hat{x}_{k|k} = \hat{x}_{k|k-1} + K_k \tilde{y}_k
\]
\[
P_{k|k} = (I - K_k H_k) P_{k|k-1}
\]

It’s “odometry” because you’re continuously adding PSD matrices, meaning errors (eigenvalues) grow without bounds

A rover cannot drill into a rock if it is 100m away from it after a day’s drive.
Global Localization

ai.jpl.nasa.gov
The only source of global localization to date: Rectified orbital imagery
The only source of global localization to date: Rectified orbital imagery

... and people

Luckily, we can see MSL in this image. Usually, you do not have a fresh shot, so you have to match terrain.
Let’s automate that!

Topographical Landmarks for Ground-Level Terrain Relative Navigation on Mars

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What if …

- Take a global map
- Find a bunch of peaks
- Take onboard images
- And a few bearings
1. Global Map

• Believe it or not, elevation maps for Mars exist and are fairly easy to find
• https://pds.jpl.nasa.gov/
2. Find peaks

- downsample to appropriate resolution (e.g. 50m/px)
- classify terrain features with GRASS r.param.scale
- extract, cluster, and merge peaks into polygons
- extract centroids
- dilate and merge polygons (reduces discretization artifacts)

https://github.com/rschwa6308/Landmark-Based-TRN
3. Detecting Peaks in Rover Imagery

- Skyline delineation using semantic Segmentation for planetary robotic explorers (PERs)
- Demonstrate segmented skyline can be used for terrain relative navigation (TRN)
  - Compare to known Digital Elevation Model (DEM) data
- Semantic Segmentation using DeepLab V3+
  - Segment **terrain** from **sky**
- Method enables:
  - Monocular camera localization
    > Terrain Relative Navigation (TRN)
    > GPS-denied areas
  - Multi-agent operation
    > Cohort detection

Toward Autonomous Localization of Planetary Robotic Explorers by Relying on Semantic Mapping

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2021-04-20
This document has been reviewed and determined not to contain export controlled information.
CL#22-1899
3. Detecting Peaks in Rover Imagery

- Frameworks & Architectures:
  - DeepLab V3+ w/ MobileNet-V2 & Xception65

- Training | validation splits:
  - Mars: 20 train | 4 validations from Mars Curiosity Rover (PDS Image Atlas)
    - Two classes: ‘terrain’ and ‘sky’
    - Test set (experiments) comes from Mars Perseverance Rover

- Semantic labeling performed with labelme tool ([https://github.com/wkentaro/labelme](https://github.com/wkentaro/labelme))

- Model used for experiments:
  - DeepLab V3+ with MobileNetV2 backbone, 750 training iterations w/ batch size: 2
Semantic Segmentation Results

DeepLab V3+ MobileNetV2 @ 750 training iterations w/ batch size: 2
Inference time: 0.113 sec / image (on Colab GPU)
A fairly simple algorithm could isolate peaks from those contours you can try it, see https://github.com/dkogan/horizonator to render contours from elevation maps
Mars Perseverance's first panorama
It works!
Summary

• Given a map of known peak locations
• Take an onboard image and extract peaks from that image
  • (Take the machine learning course)
• Use the pixel coordinates to determine bearing to peak
  • (Take the computer vision course)
• Use bearings to estimate the rover’s location on Mars

• Question: How well does this work? And when won’t it work?
Estimating informativeness

• Suppose you know where you want to drive, but want to know if the rover could localize itself along that drive
• Or, suppose you wanted to know where to land so that you can get a quick nav fix

• We need an *informativeness* metric that includes:
  1. Rover’s possible location
  2. Visibility of landmarks rover can use (visible/not visible)
  3. A cost function which rolls up the expected nav error given 1, 2

  Hint: GDOP!
Estimating informativeness

• Suppose you know where you want to drive, but want to know if the rover could localize itself along that drive
• Or, suppose you wanted to know where to land so that you can get a quick nav fix

• We need an informativeness metric that includes:
  1. Rover’s possible location (Just use a whole area or trajectory)
  2. Visibility of landmarks rover can use (visible/not visible)
  3. A cost function which rolls up the expected nav error given 1, 2
2. Visibility of Landmarks

• Called the “viewshed”

• Geographic Information Systems (GIS) software like ArcGIS (right) and others will do this for you, given an elevation map

• We used QGIS
  https://www.qgis.org/en/site/
EKF equations (Wikipedia)

\[
\hat{x}_{k|k-1} = f(\hat{x}_{k-1|k-1}, u_k)
\]

\[
P_{k|k-1} = F_k P_{k-1|k-1} F_k^T + Q_k
\]

\[
\tilde{y}_k = z_k - h(\hat{x}_{k|k-1})
\]

\[
S_k = H_k P_{k|k-1} H_k^T + R_k
\]

\[
K_k = P_{k|k-1} H_k^T S_k^{-1}
\]

\[
\hat{x}_{k|k} = \hat{x}_{k|k-1} + K_k \tilde{y}_k
\]

\[
P_{k|k} = (I - K_k H_k) P_{k|k-1}
\]

Deriving “informativeness”

\[
P_+ = (I - KH) P
\]

(Apply Matrix Inversion Lemma)

\[
P_+ = P - PH^T (HPH^T + R)^{-1} HP
\]

(insert K, S definitions)

\[
P_+ = (P^{-1} + H^T R^{-1} H)^{-1}
\]

Just add one 2x2 matrix for each peak to get new covariance

https://robotics.stackexchange.com/questions/1180/information-filter-instead-of-kalman-filter-approach/1185#1185
3. Informativeness of observations

If you know where the rover is (or could be), you can estimate the terms of the sum from the peaks that are visible …

We derive the “priorless” covariance ellipse centered on our true position, which shows the distribution of errors that any decent filter will have.

This is called
Geometric Dilution of Precision (GDOP)
Fisher Information
Cramer-Rao Lower Bound

For reference, typical GDOP for GPS is ~10 meters.

From previous slide, and assume no prior

\[
P^{-1}_+ = R^{-1} + H^T R^{-1} H
\]

\[
C^{-1} = \sum_{i=1}^{N} \frac{1}{\eta_i^2 \sigma_i^2} \begin{bmatrix}
\sin^2 \alpha_i & -\sin \alpha_i \cos \alpha_i \\
-\sin \alpha_i \cos \alpha_i & \cos^2 \alpha_i
\end{bmatrix}
\]
3. Informativeness of observations

Start with a digital elevation map (DEM) of the region in question.

Extract peaks on that map

For each point on the map

• Calculate which peaks are visible
• Calculate bearings to the peaks
• Plug into CRLB/GDOP

We developed a set of processing plugins for QGIS which automate this process.

Example Right: Catalina Island. Note that NW/SE is “bad” because the peaks are colinear, and that in general closer is better.
Informative locations in Jezero Crater
JPL is a diverse place, with people of all backgrounds and walks of life.

We support a huge variety of projects, including Defense, Science, and Exploration of the Earth and Solar System.

The AI Group(s) needs grads with:

- **Computer Science**
- Software engineering
- Combinatorial optimization
- Algorithm design & analysis
- *ML not required*
- TS/SCI clearance helpful for some projects!

ai.jpl.nasa.gov
ml.jpl.nasa.gov
dus.jpl.nasa.gov

josh.vanderhook.info/talks
credits

- https://www.youtube.com/watch?v=E3xWCqPBUFU
- https://www.youtube.com/watch?v=5qqsMjy8Rx0
- https://trs.jpl.nasa.gov/bitstream/handle/2014/47704/CL%2317-1496.pdf?sequence=1