ME/CS 132:
Introduction to
Vision-based Robot Navigation

Course Objectives and Scope

- Introduction to vision-based navigation for robotic vehicles
- 2-quarter sequence
  - Winter: vision, state estimation, and mapping
  - Spring: motion planning and control
- Problem sets, programming assignments, and week-long mini-projects each quarter, plus group project in spring quarter
- Projects will “operate” the Player/Stage robot simulator and Pioneer robots
- Winter term evaluation: 60% homeworks, 20% each for 2 week-long mini-projects

Instructors

- Lectures by JPL personnel, with general support from Prof. Joel Burdick
- http://robotics.jpl.nasa.gov/people/... for photos and more info


Larry Matthies

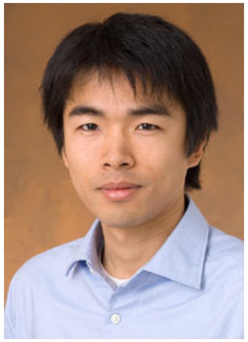

Adnan Ansar


Roland Brockers


Yang Cheng


Tom Howard


Nick Hudson

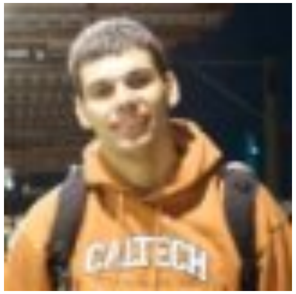

Yoshi Kuwata


Jeremy Ma


Brian Williams


Joel Burdick

TAs, Logistics, Prerequisites



- Lectures: Tue/Thu, 2:30-4 pm, 306 Thomas
- Office hours: Tue/Thu, 4-5 pm, 303 Thomas
- TAs:
  - Andrea Censi, Shuo Han (me132-tas@caltech.edu)
  - Office hours: TBD
- Course wiki:
  - www.cds.caltech.edu/~murray/wiki/index.php/ME/CS_132a,_Winter_2010
- Course mailing list: me132-students@caltech.edu (sign up on wiki)
- Recommended background:
  - ME 115ab (Introduction to Kinematics and Robotics)
  - Basic understanding of linear algebra, probability, and statistics
  - Programming experience with Matlab and C; Python optional

Texts and Supplemental Material

- Texts (free downloads):
  - Richard Szeliski, *Computer Vision: Algorithms and Applications*, http://szeliski.org/Book
  - Steven M. LaValle, *Planning Algorithms,* http://planning.cs.uiuc.edu
- Additional reference texts (optional, you'll have to buy them):
  - D. Forsyth and J. Ponce, Computer Vision: *A Modern Approach*
  - S. Thrun, W. Burgard, and D. Fox, *Probabilistic Robotics*
- Reading for this week:
  - Szeliski, ch. 1: Introduction (optional)
  - Szeliski, sec. 2.2: Photometric image formation (next lecture)
  - Forsyth, ch. 1 (free pdf): Cameras (for next Tuesday -- Jan 11)

Motivating Application: Mars Surface Exploration

Why explore Mars?

W A T E R

When

Where

Form

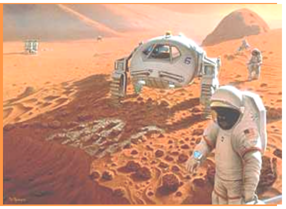
Amount

Look for Life

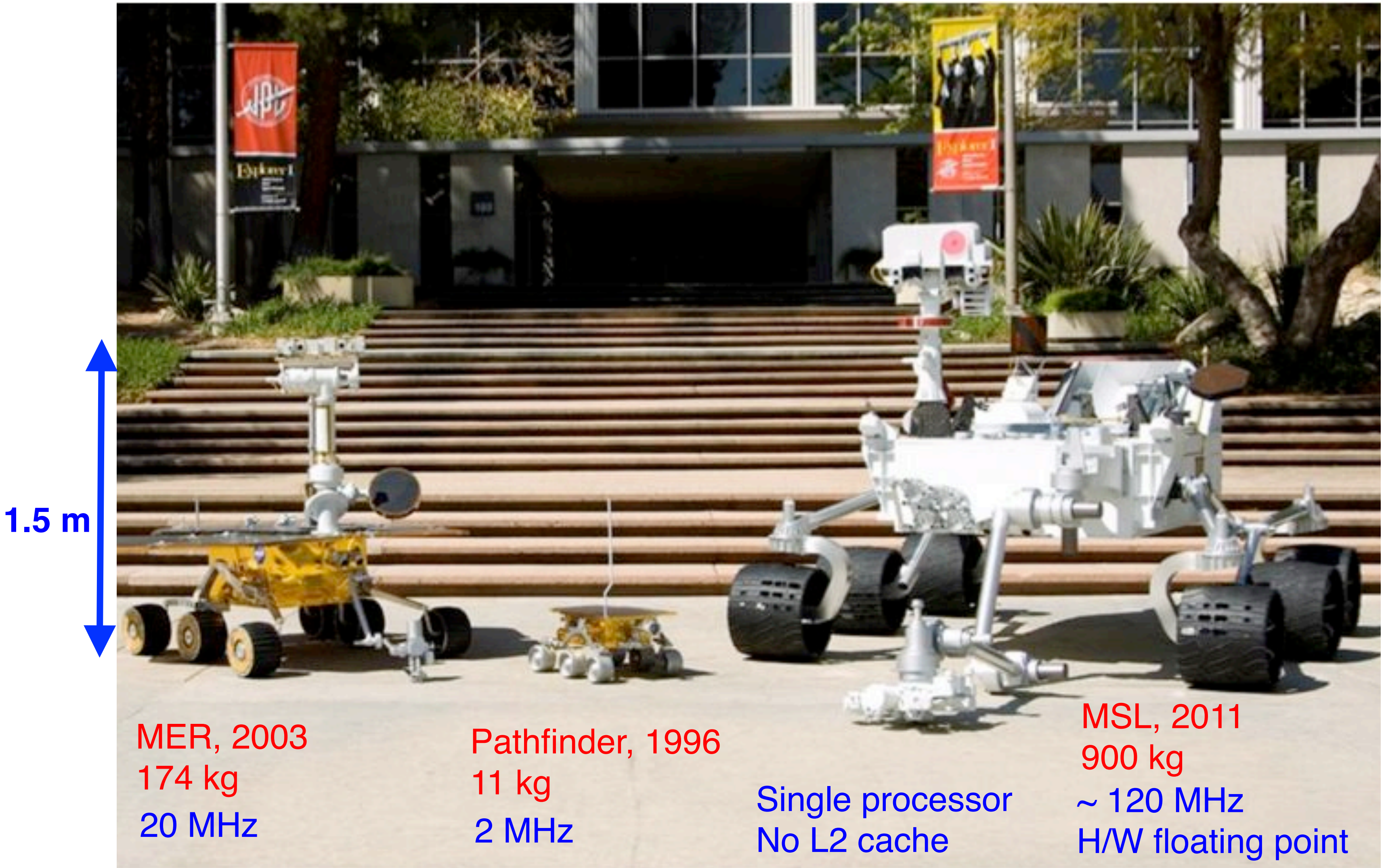
Understand Climate

Explore Geology

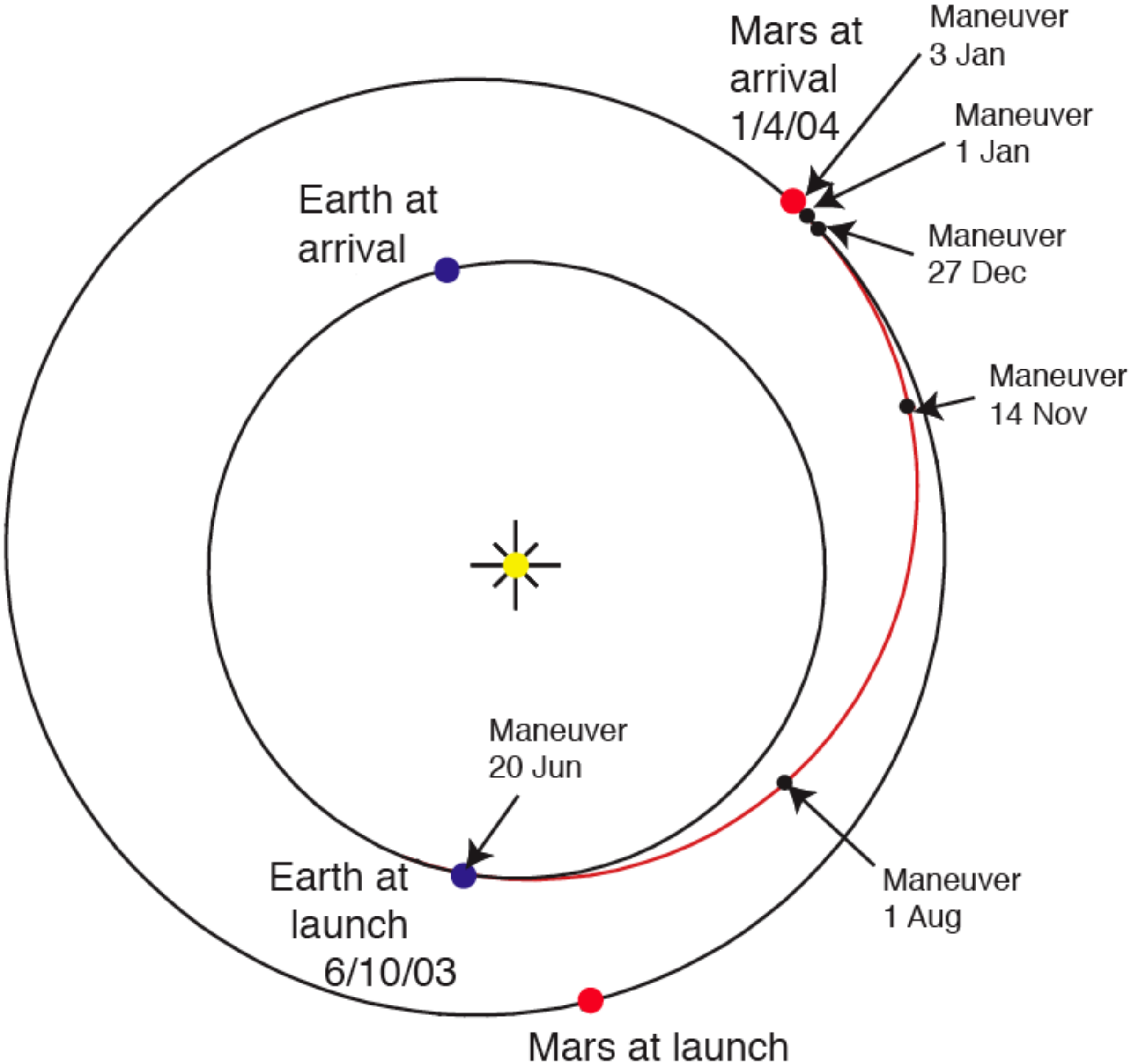
Prepare for Human Exploration



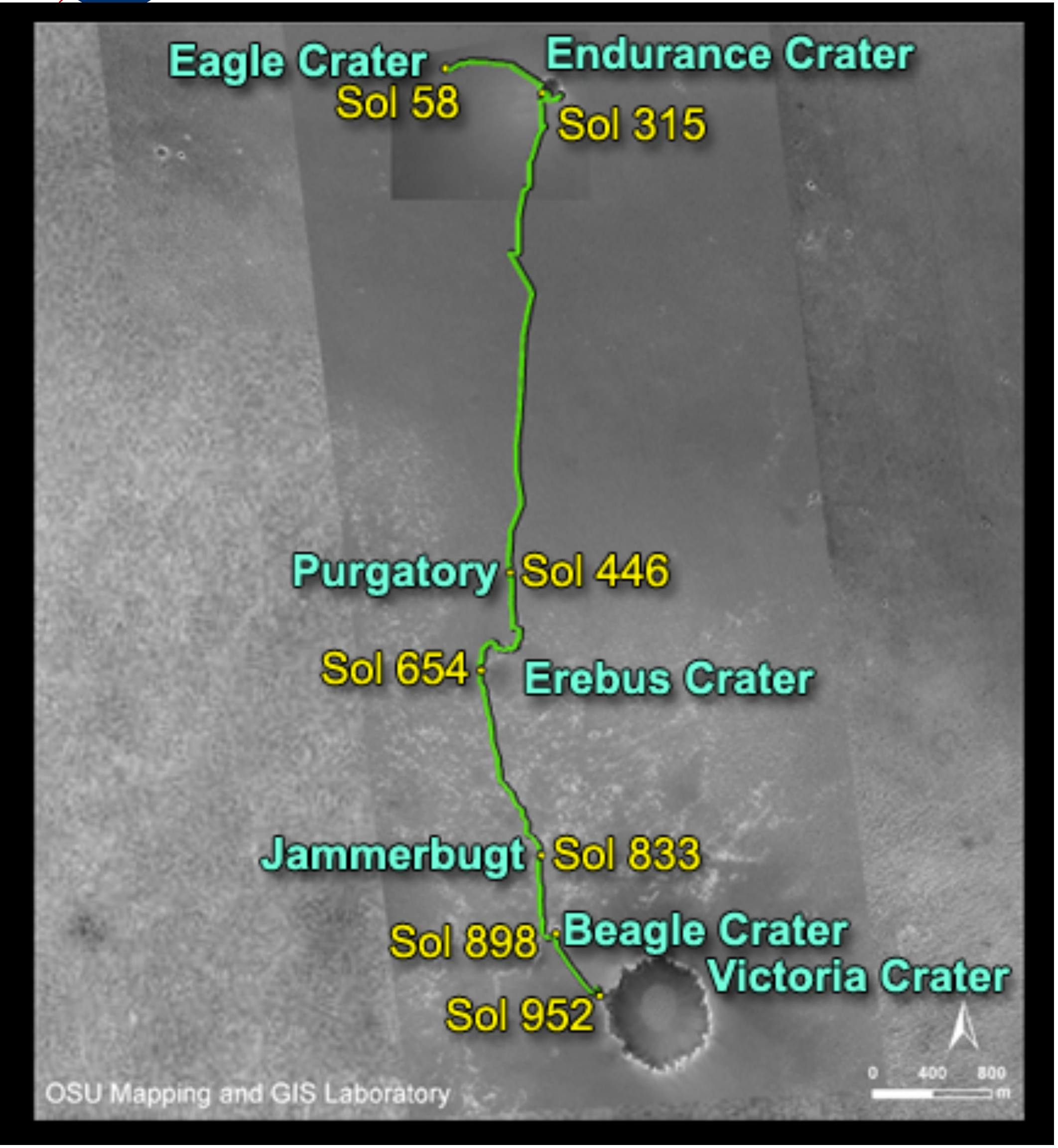
Recent and Future NASA Mars Rovers

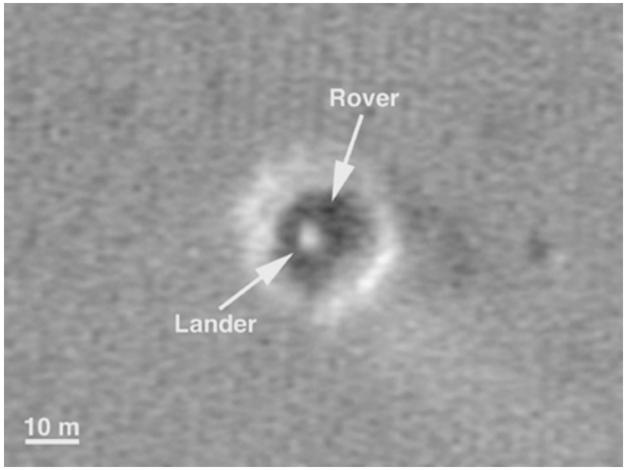


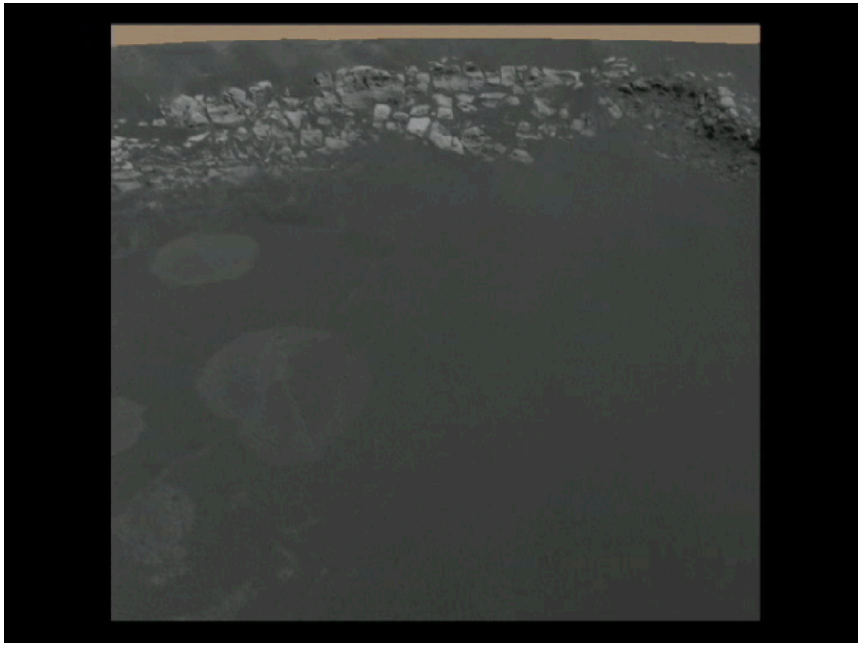
Why Must Mars Rovers Have Autonomy?



What Do Rovers Do?



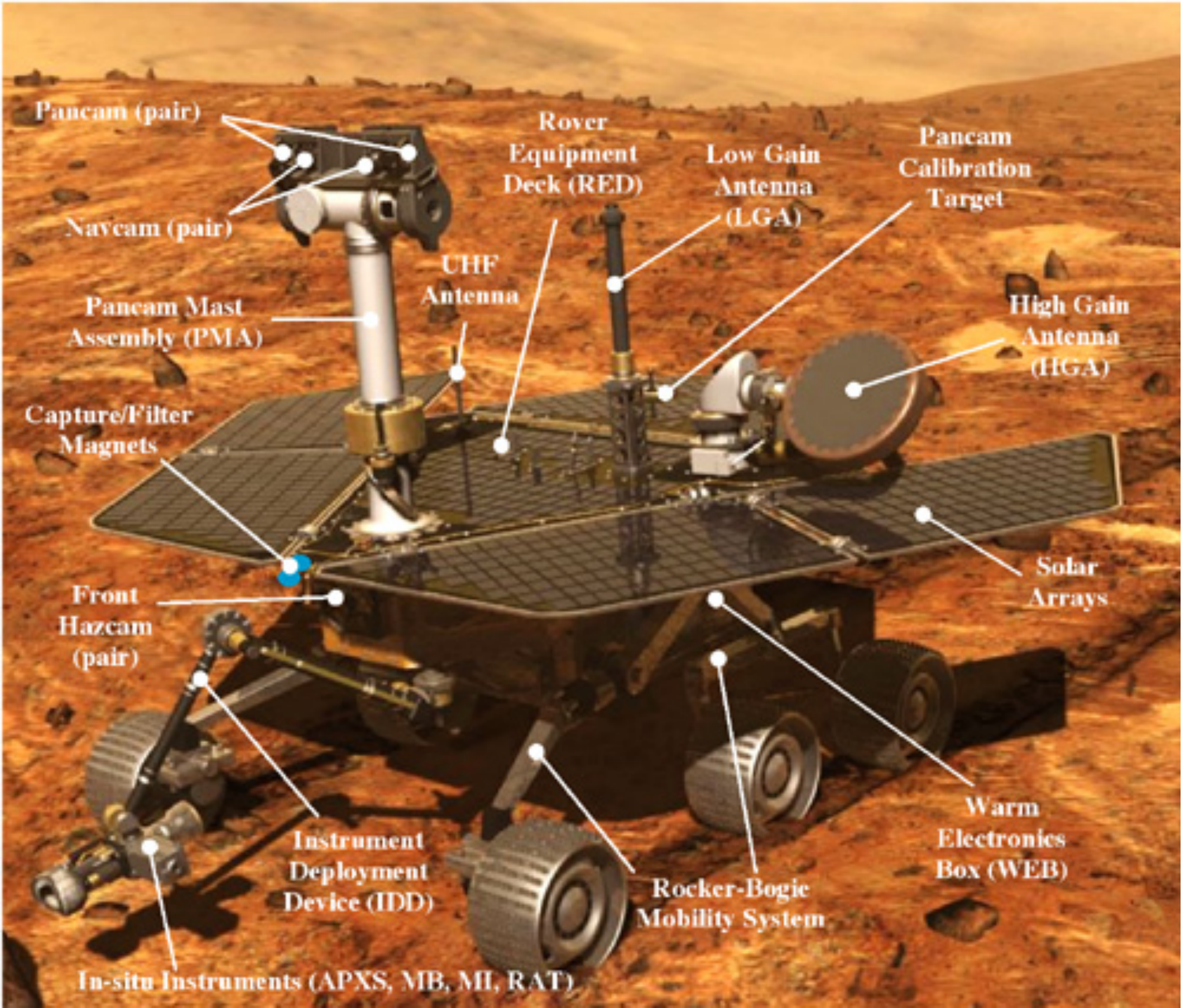




Elements of Autonomous Navigation

- Subproblems:
    - Where am I?
    - Where is my goal?
    - What’s in the way between my goal and I?
    - What am I going to do when I get to the goal?
    - What path should I take to the goal?
    - How do I execute the drive to the goal?
- Subsystems:
    - Sensors and algorithms for state estimation
    - Sensors and algorithms for terrain perception and mapping
    - Algorithms for planning and control

Mars Exploration Rover Components



1.1 m wheelbase
1.0 m trackwidth

174 kg

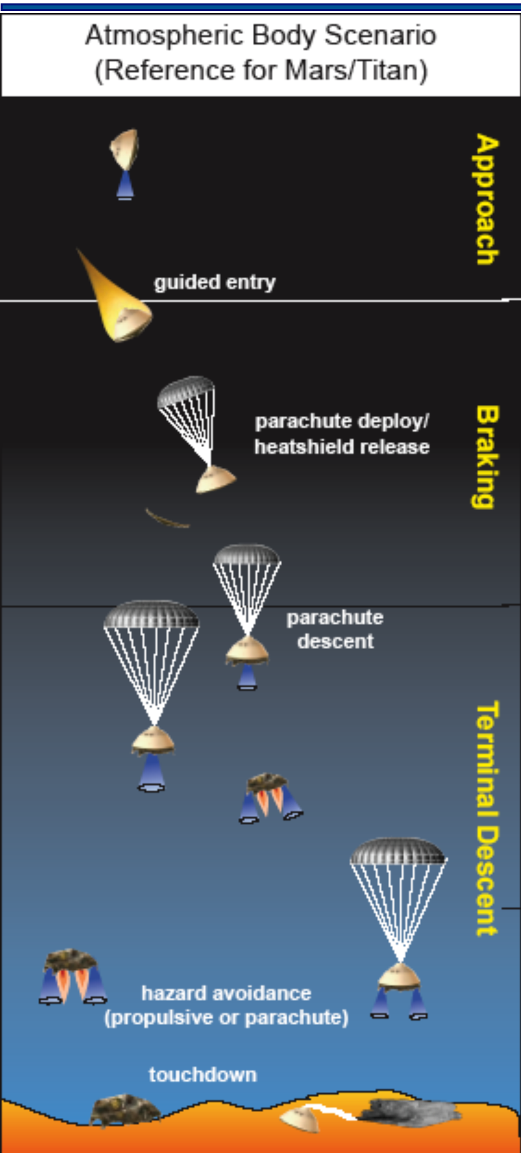
5 cm/sec velocity

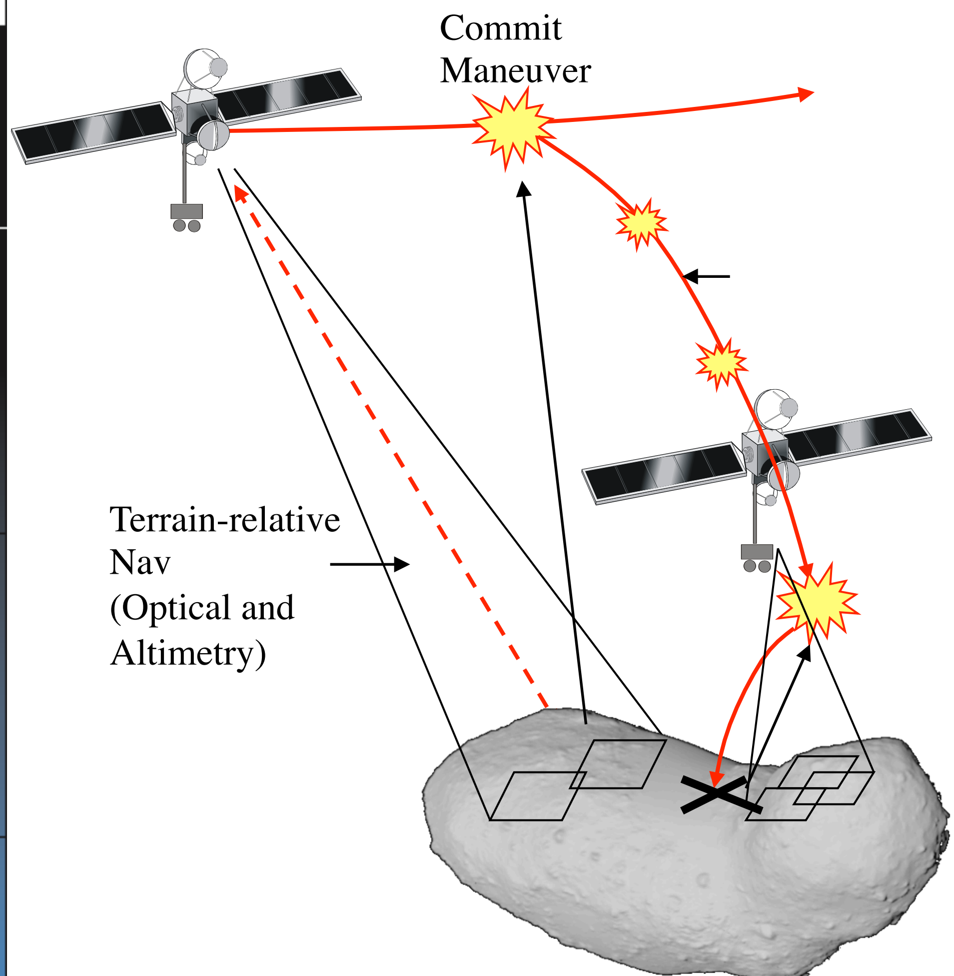
Rocker bogey suspension;
25 cm step climb

20 MHz RAD6000 processor,
128 MB RAM
256 MB flash

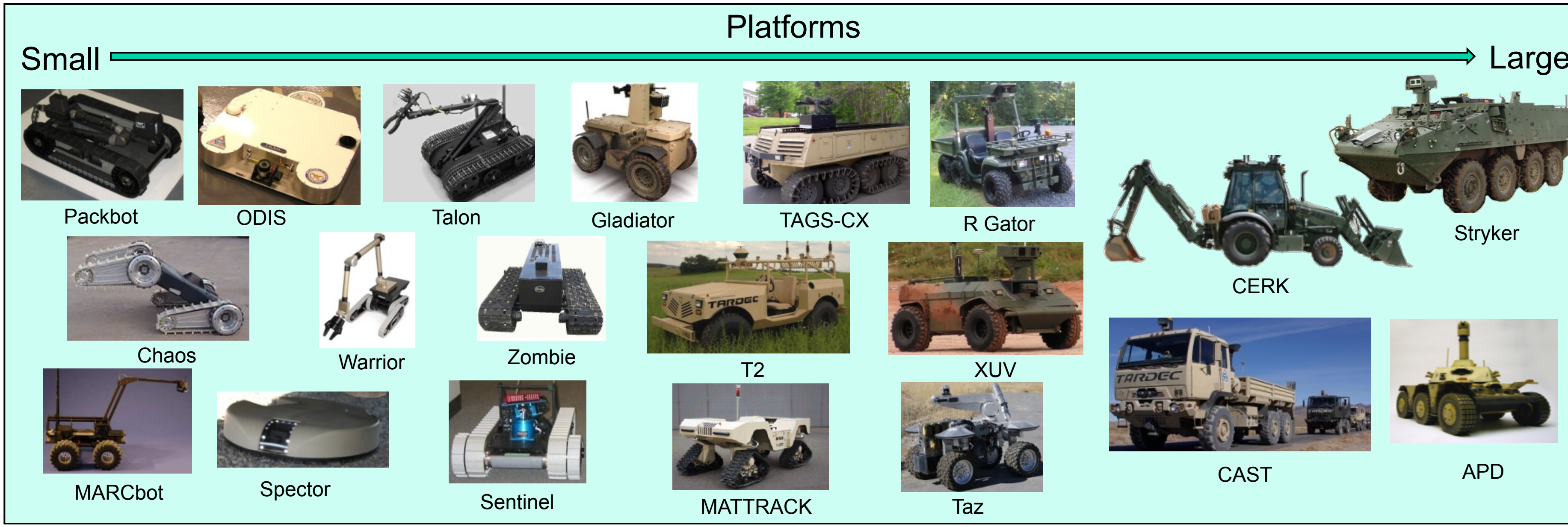
Cameras:
1024x1024,
12 bits/pixel

Other Applications in Solar System Exploration



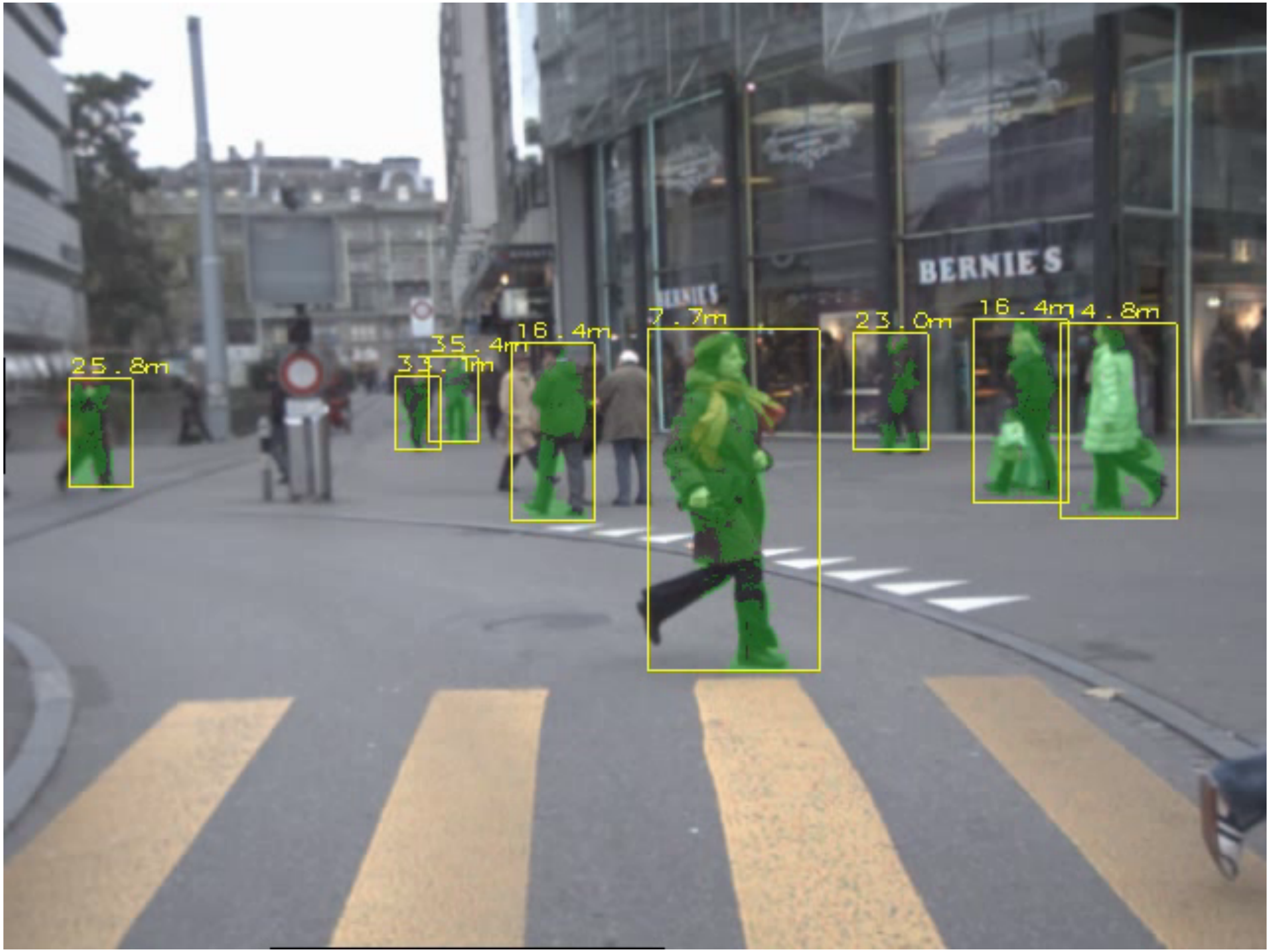


UGV Applications in DoD/DHS

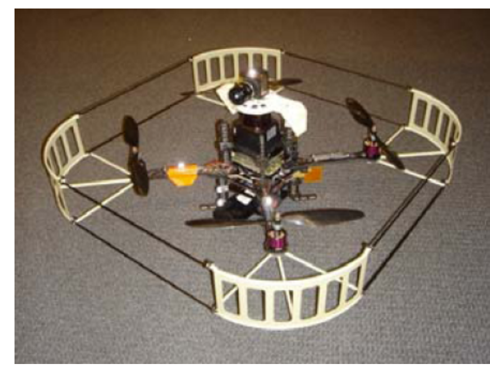


UGV Applications in DoD

UGV Applications in DoD



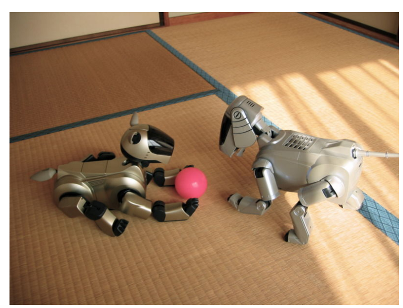
UAV Applications in DoD and Civil

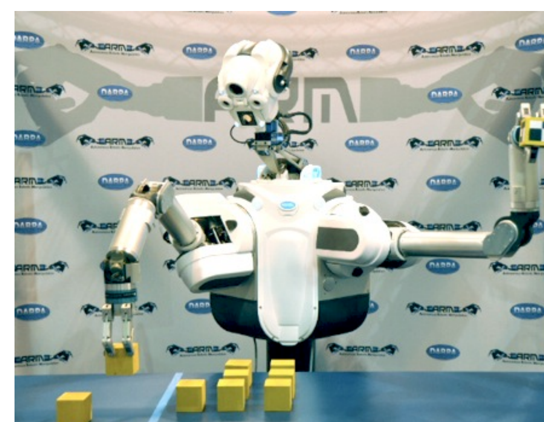


Civil and Commercial Applications

- http://www.mobileye.com/
- Vision systems currently in high-end BMW, GM, Volvo models

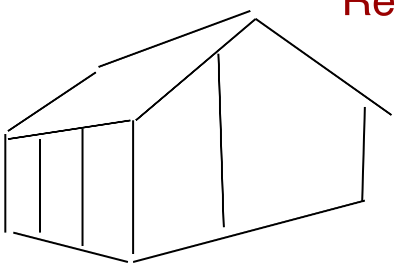
Civil and Commercial Applications

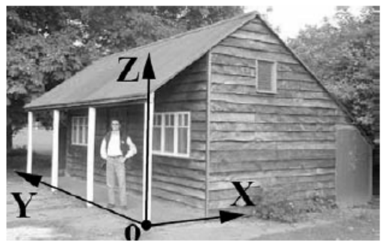




Course Philosophy

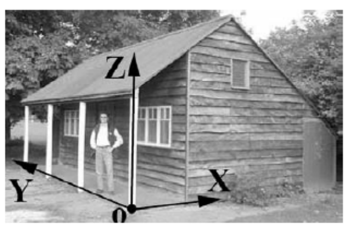
Rendering





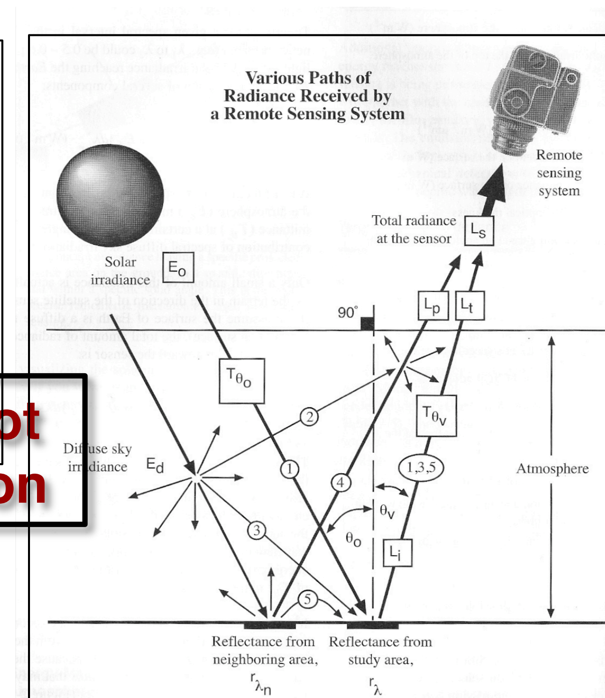
Computer graphics

Estimation



Computer vision

Robot vision



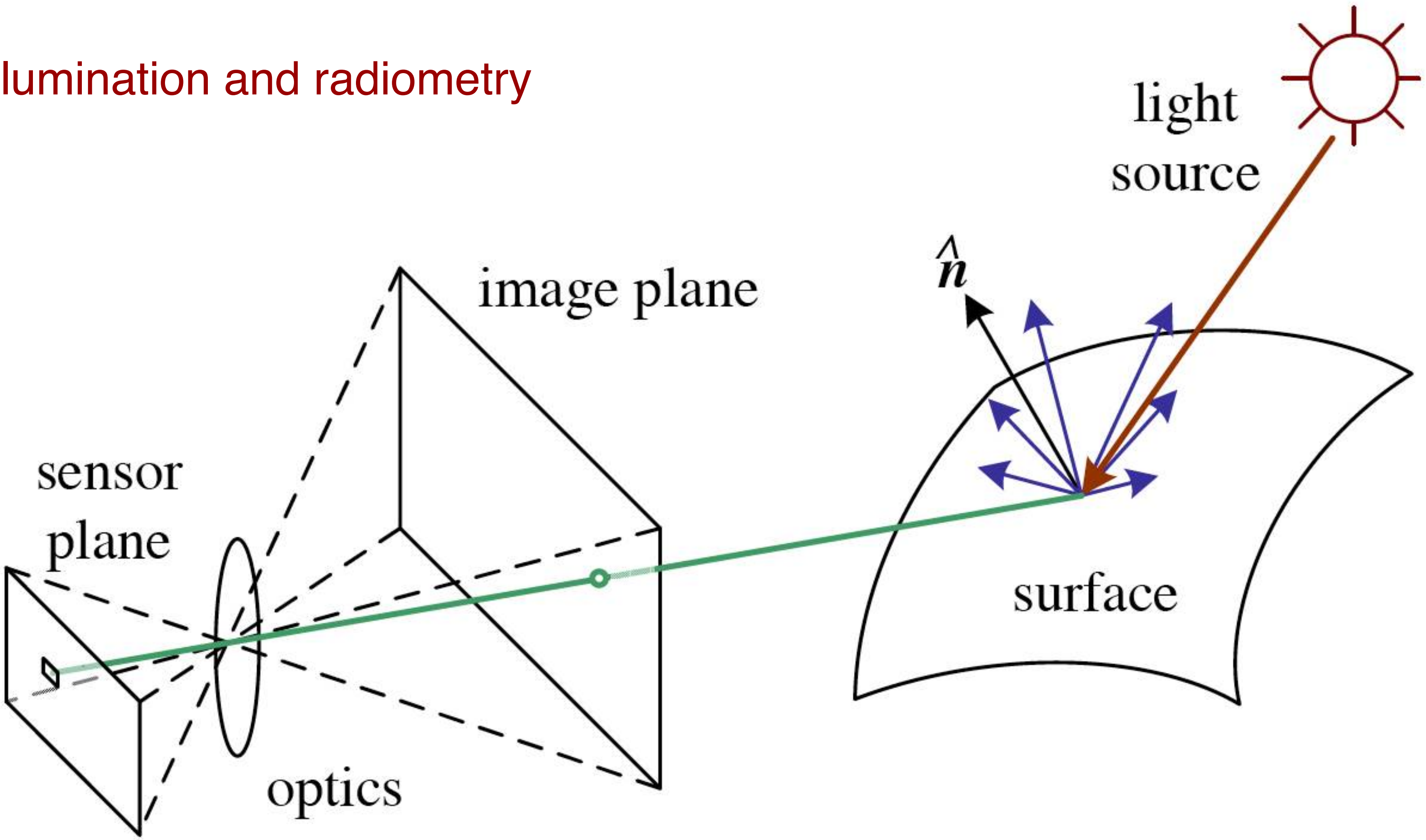
Remote sensing

Syllabus: Winter Quarter

- Image formation, cameras, and camera calibration
  - Illumination and radiometry
    - Sources of light – sunlight, thermal emission, night sky glow
    - Propagation of light – reflection from surfaces, attenuation in media
  - Cameras
    - Basic optics
    - Camera architectures
    - Image detectors – materials, architectures, performance, for various regions of the EM spectrum
  - Geometric camera modeling and calibration

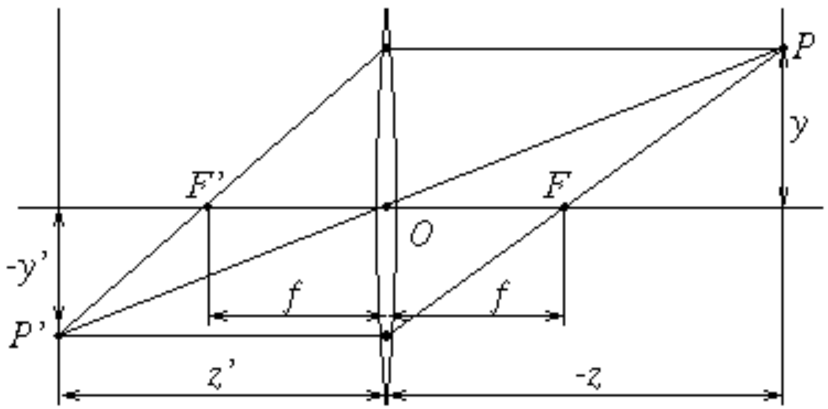
Syllabus: Winter Quarter

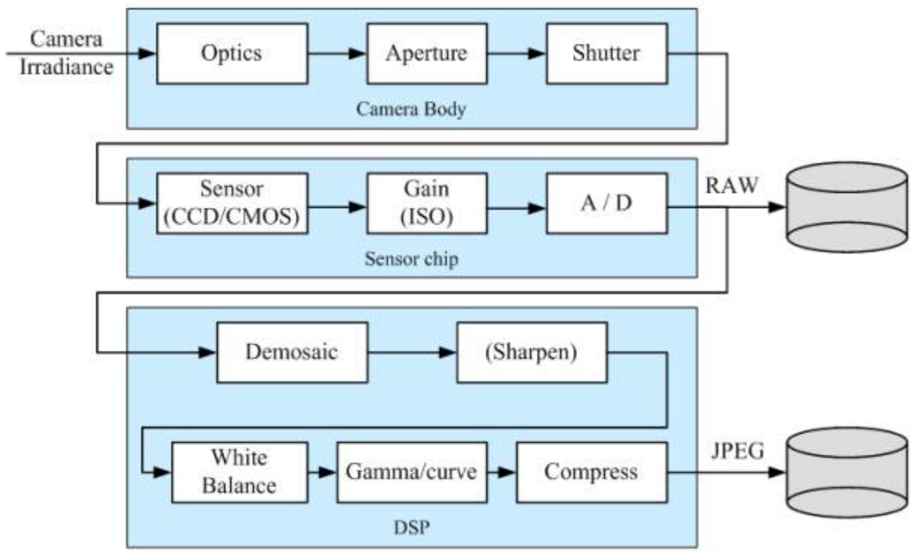
Illumination and radiometry

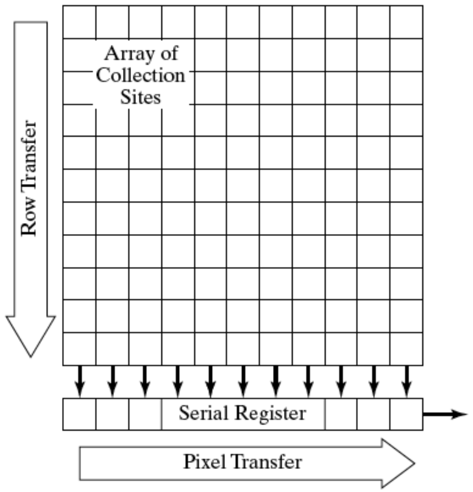


Syllabus: Winter Quarter

Cameras







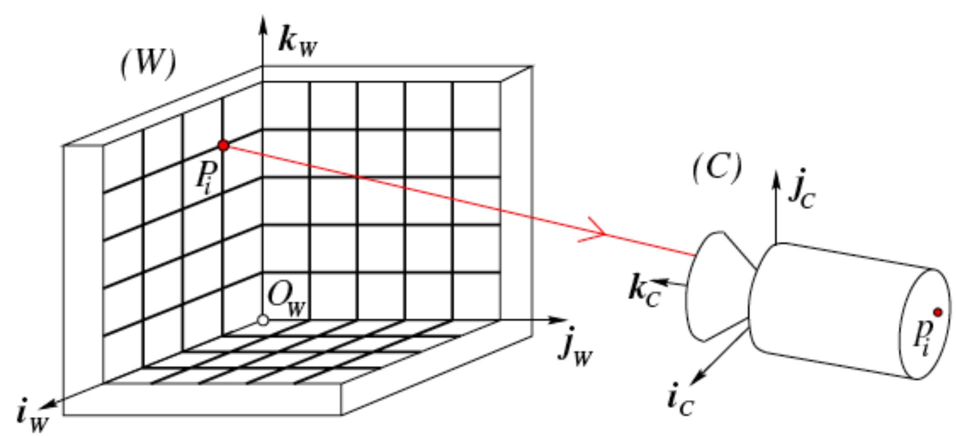
- Quantum efficiency
- Shot noise
- Dark current
- …

Syllabus: Winter Quarter

Geometric camera models and calibration

identity matrix

$$\mathbf{\Pi} = \underbrace{\begin{bmatrix} -fs_x & 0 & x'_c \\ 0 & -fs_y & y'_c \\ 0 & 0 & 1 \end{bmatrix}}_{\text{intrinsics}} \underbrace{\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}}_{\text{projection}} \underbrace{\begin{bmatrix} \mathbf{R}_{3x3} & \mathbf{0}_{3x1} \\ \mathbf{0}_{1x3} & 1 \end{bmatrix}}_{\text{rotation}} \underbrace{\begin{bmatrix} \mathbf{I}_{3x3} & \mathbf{T}_{3x1} \\ \mathbf{0}_{1x3} & 1 \end{bmatrix}}_{\text{translation}}$$



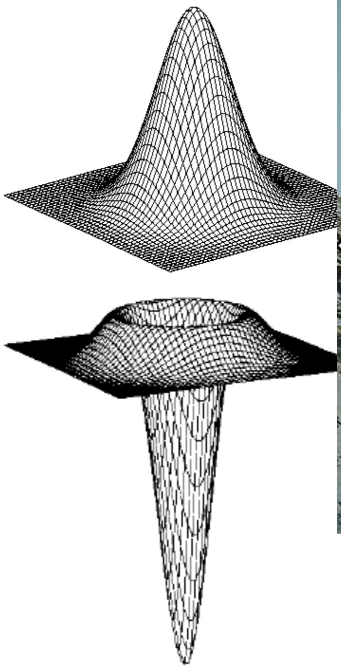
Syllabus: Winter Quarter

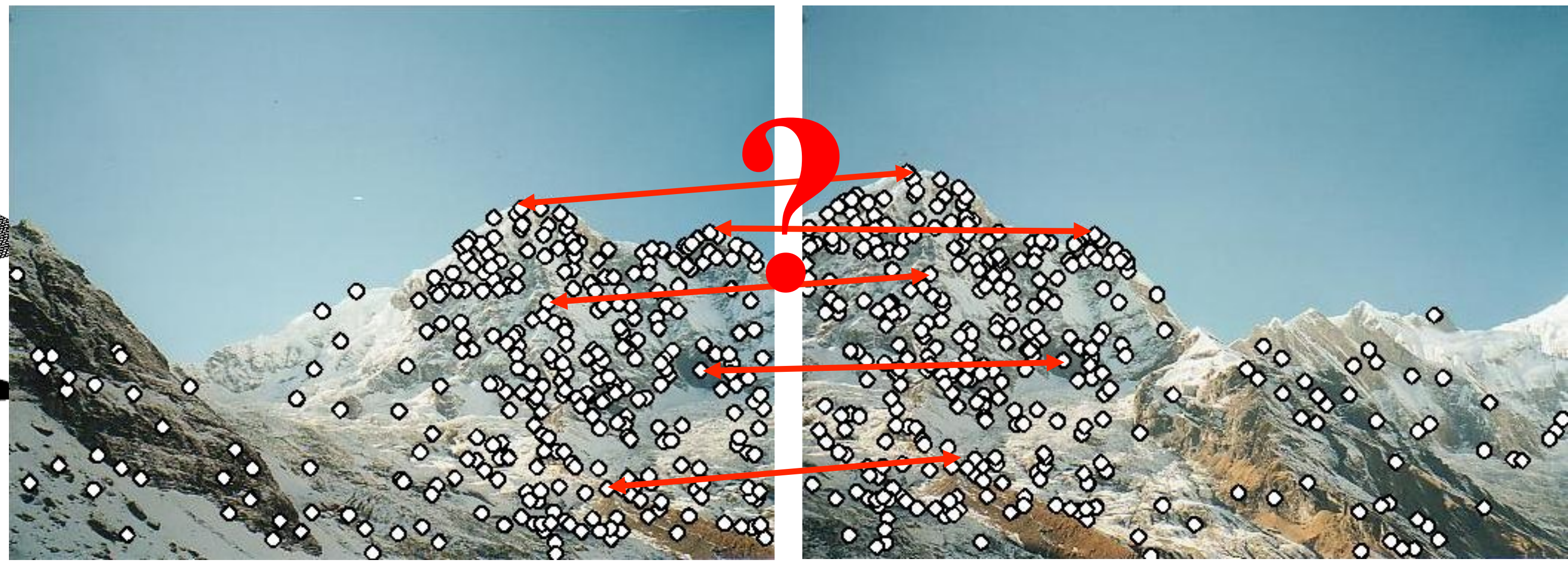
- Visual motion estimation and 3-D perception
  - Low-level image processing
  - Feature detection and matching
  - Pose estimation and visual odometry
  - Dense range imaging with stereo vision
  - Other range sensors and range data analysis

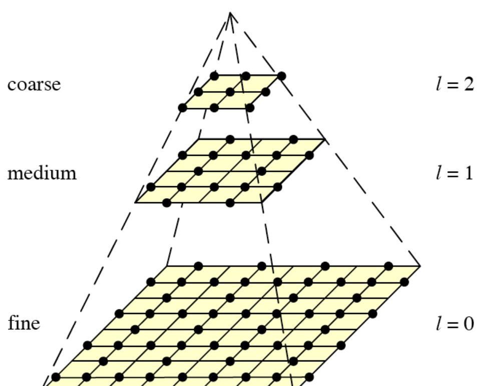
- 1-week mini-project on visual localization using a stereo camera head to match landmark points

Syllabus: Winter Quarter

Low-level image processing; feature detection and matching



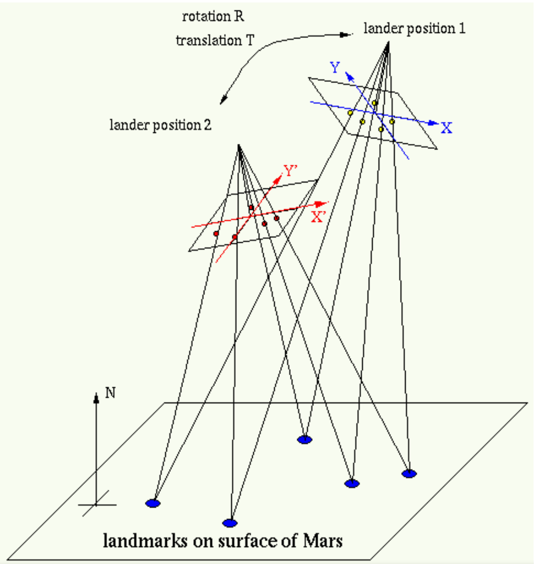


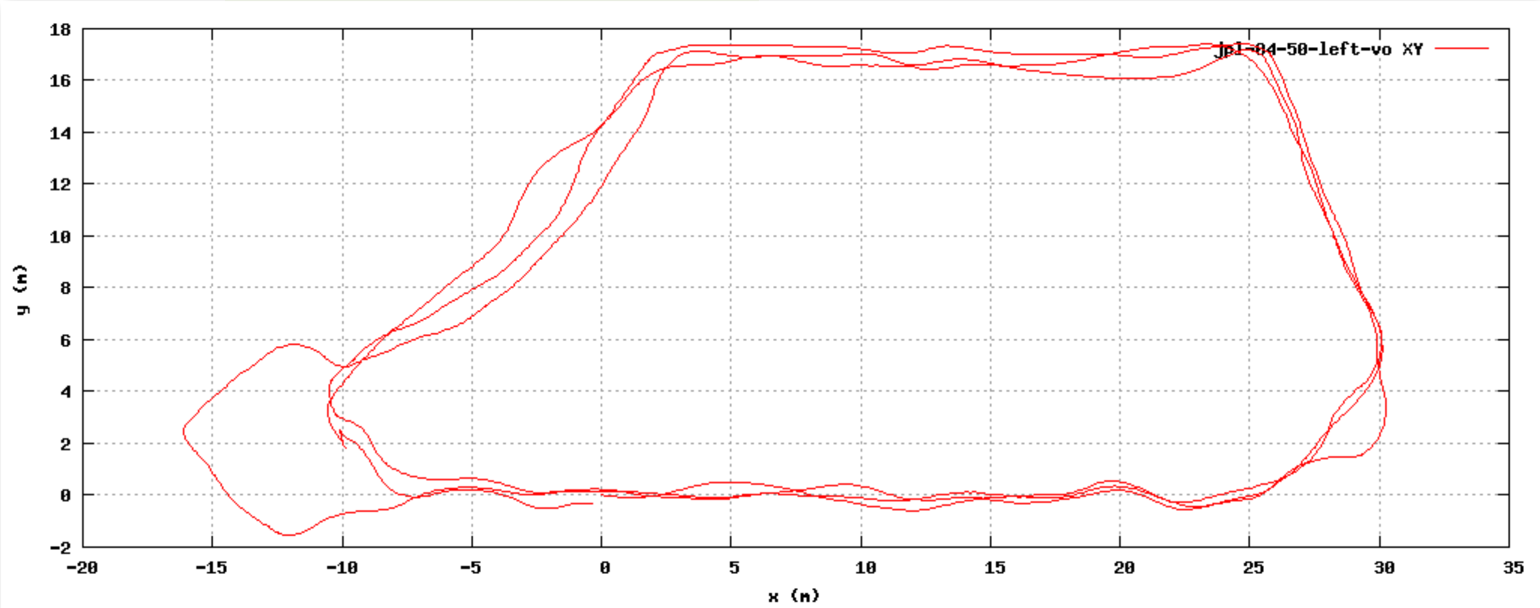


(b)

Syllabus: Winter Quarter

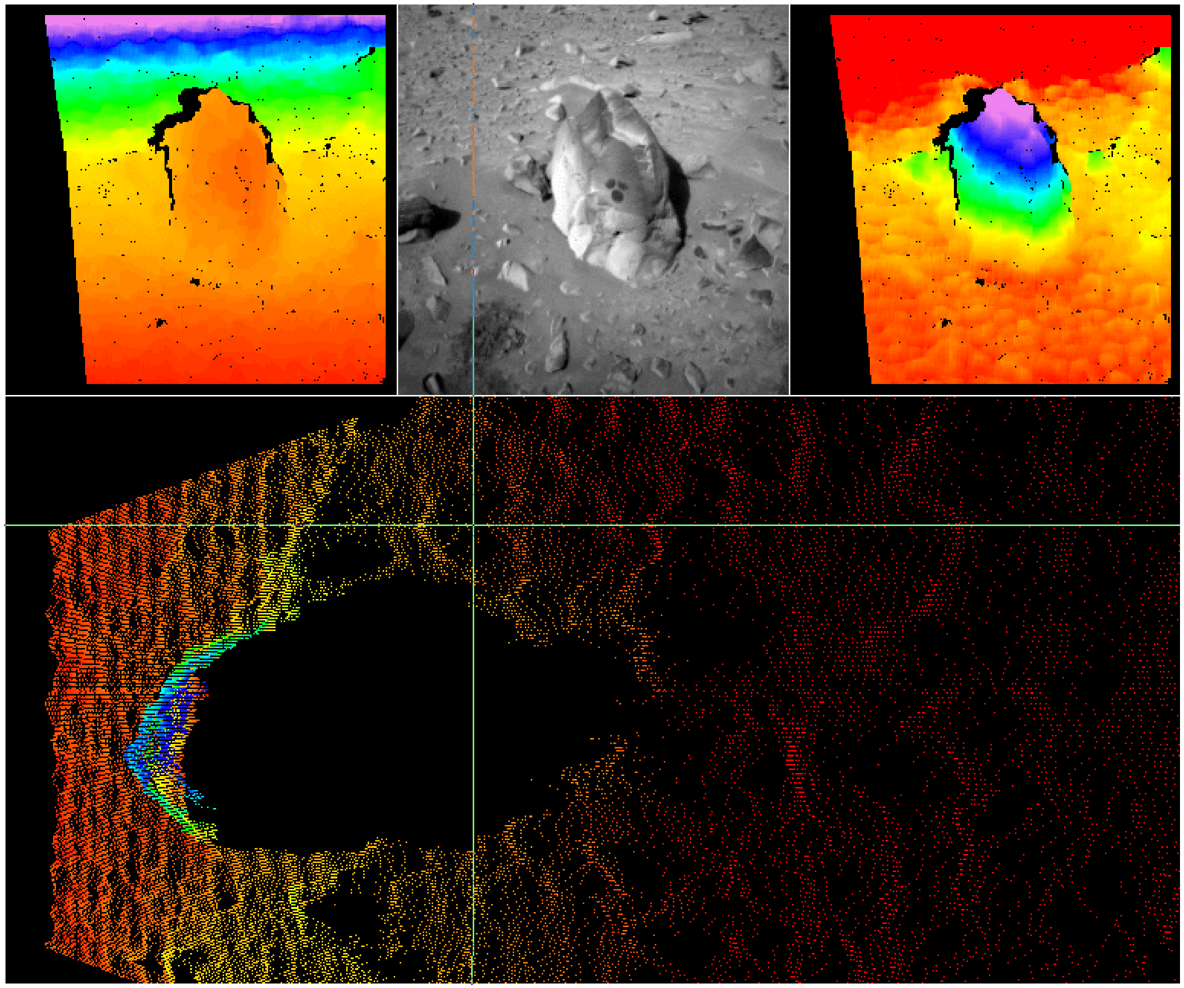
Pose estimation and visual odometry





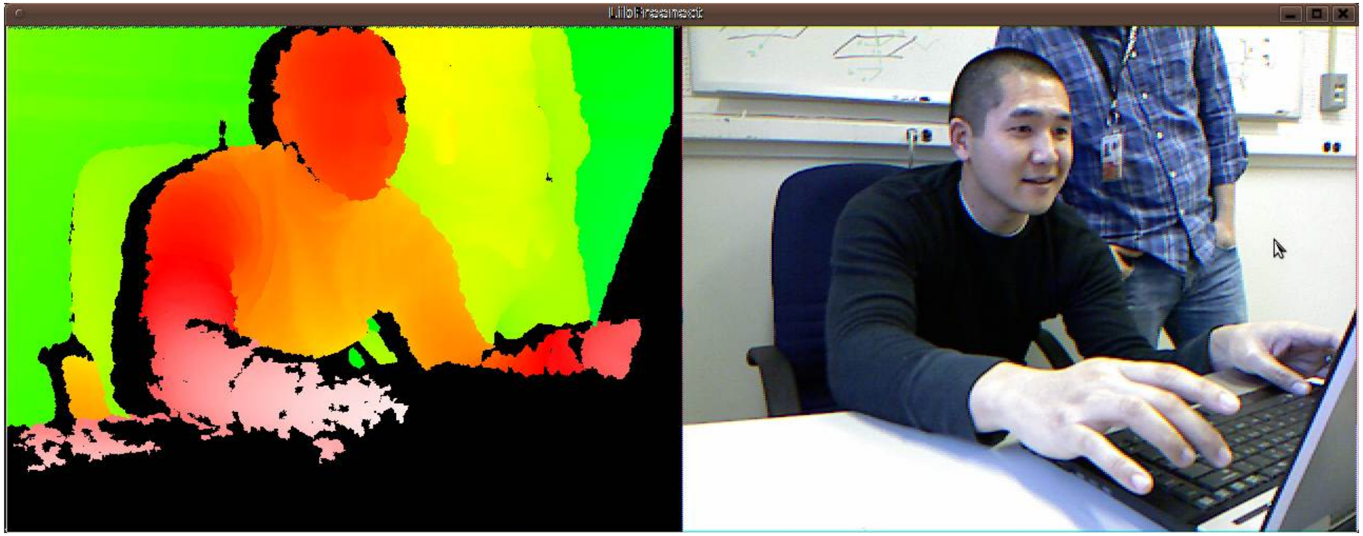
Syllabus: Winter Quarter

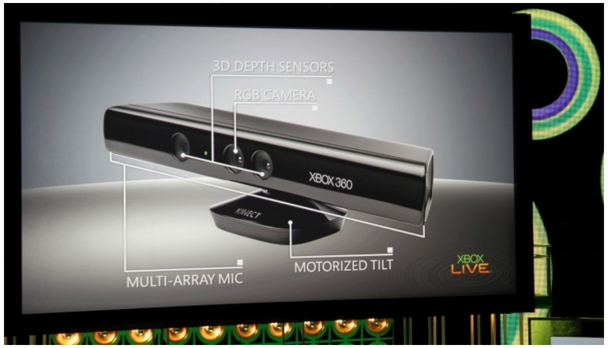
Stereo vision



Syllabus: Winter Quarter

Other range sensors and range data analysis



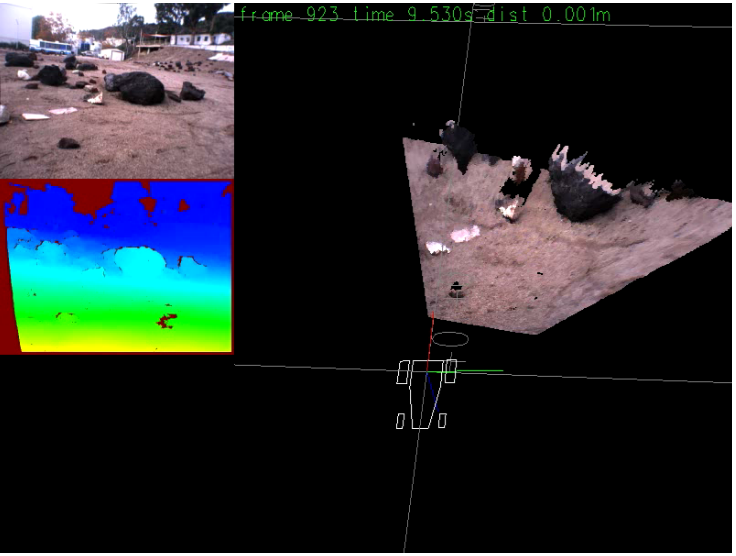


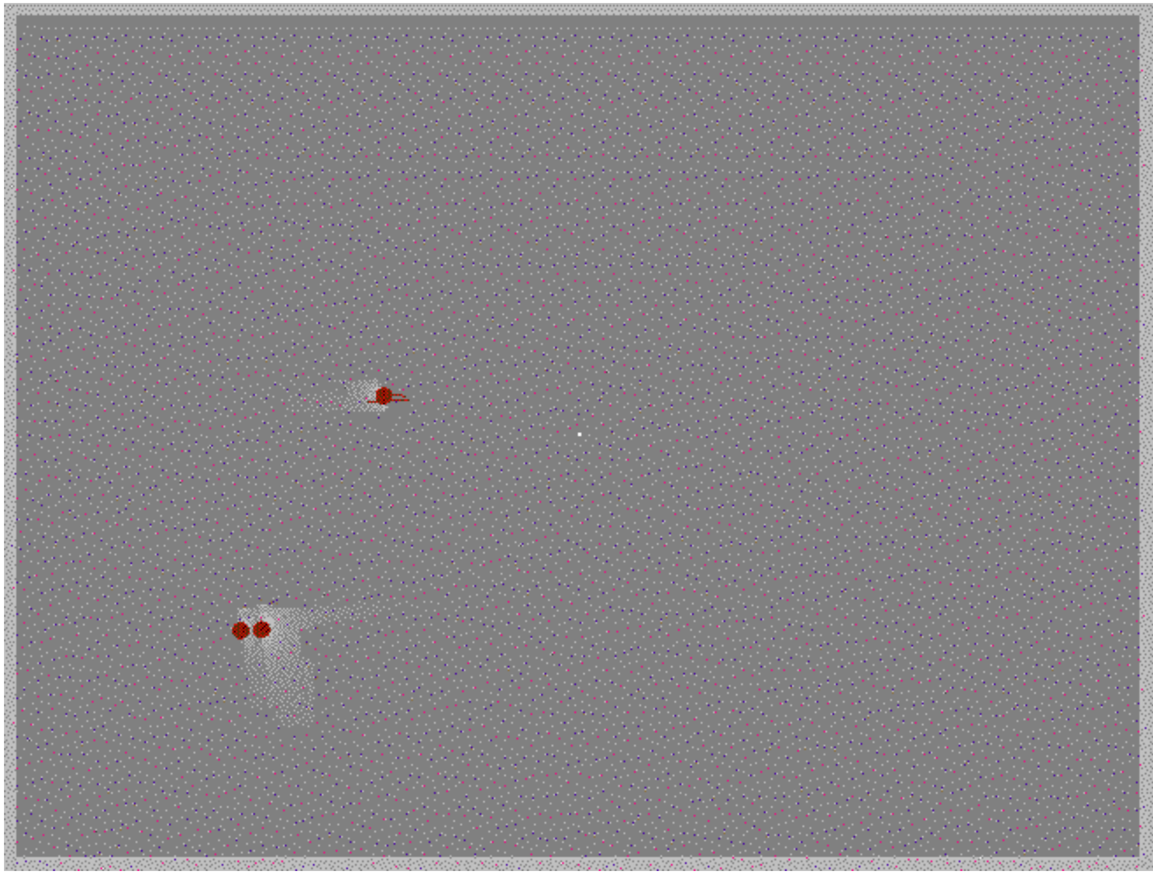
Syllabus: Winter Quarter

- State estimation, localization, and mapping
  - Introduction to estimation
  - Linear Kalman filter
  - Extended Kalman filter
  - Particle filters and the UKF
  - Simultaneous localization and mapping

- 1-week mini-project on stereo-based SLAM for localization and occupancy grid mapping with ladar

Syllabus: Winter Quarter

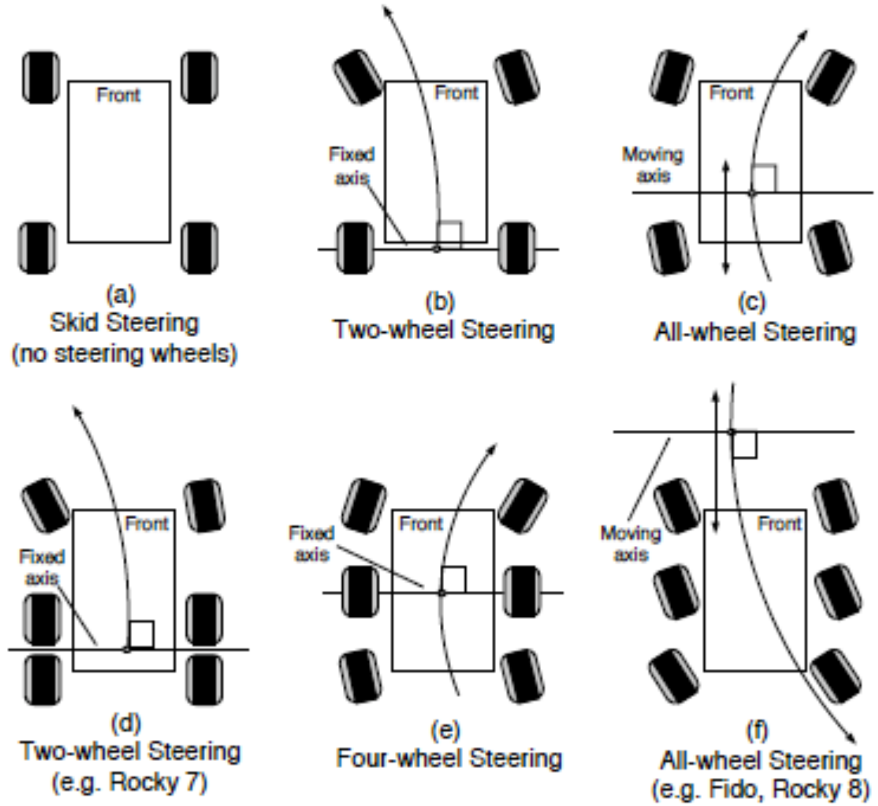


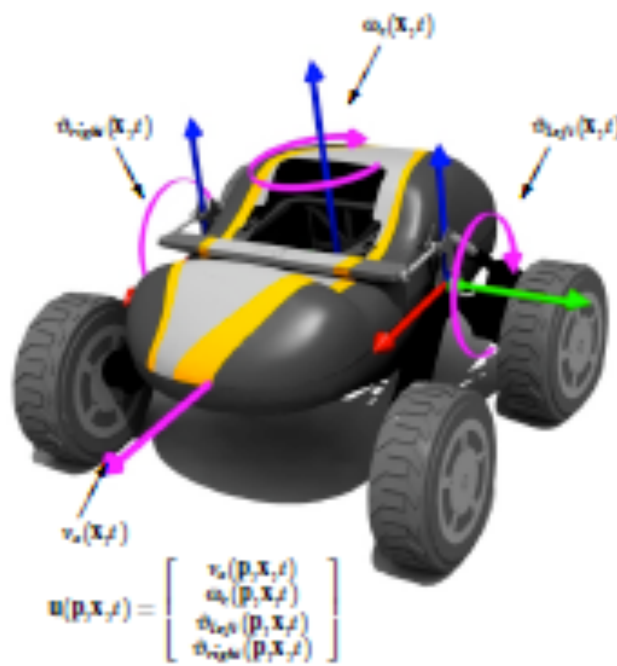


Syllabus: Spring Quarter

- Vehicle models
  – Kinematic and dynamics models
  – Motion simulation
- Motion planning and control
  – Search spaces
  – Costing
  – Search algorithms
  – Navigation and control
- 1-week mini-project on motion planning/navigation/control
- Case studies
  – Mars Exploration Rover autonomous navigation
  – Autonomous terrain relative navigation for Mars landing
- Final group project

Syllabus: Spring Quarter: Vehicle Models





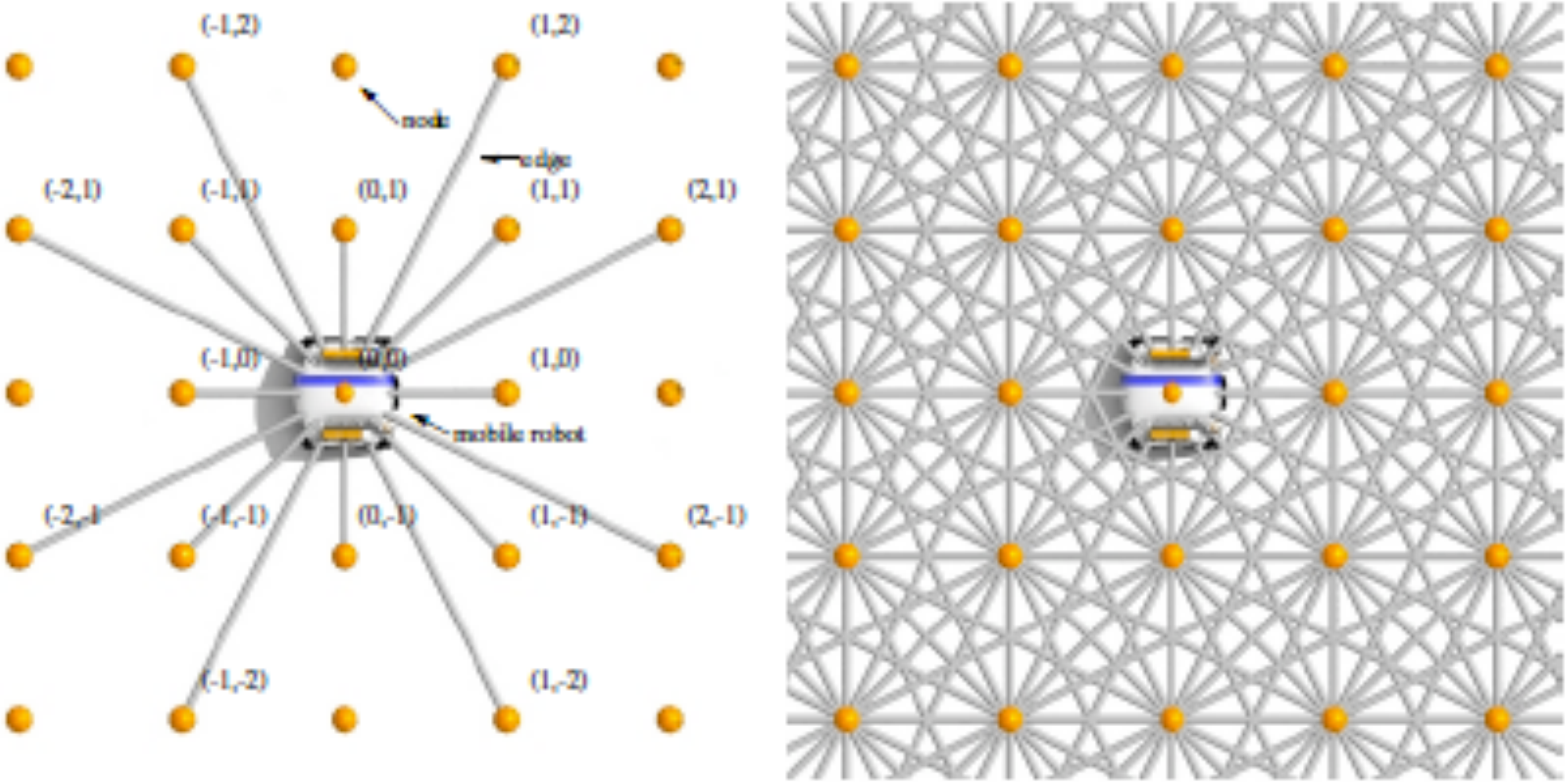
Rover Mobility Models

Figure 1 from I. A. Nesnas, M. Maimone and H. Das: Rover Maneuvering for Autonomous Vision-Based Dexterous Manipulation (2000)

Actively Articulating Mobile Robot Model

Figure 4.3b from T.M. Howard: Adaptive Model-Predictive Motion Planning for Navigation in Complex Environments (2009)

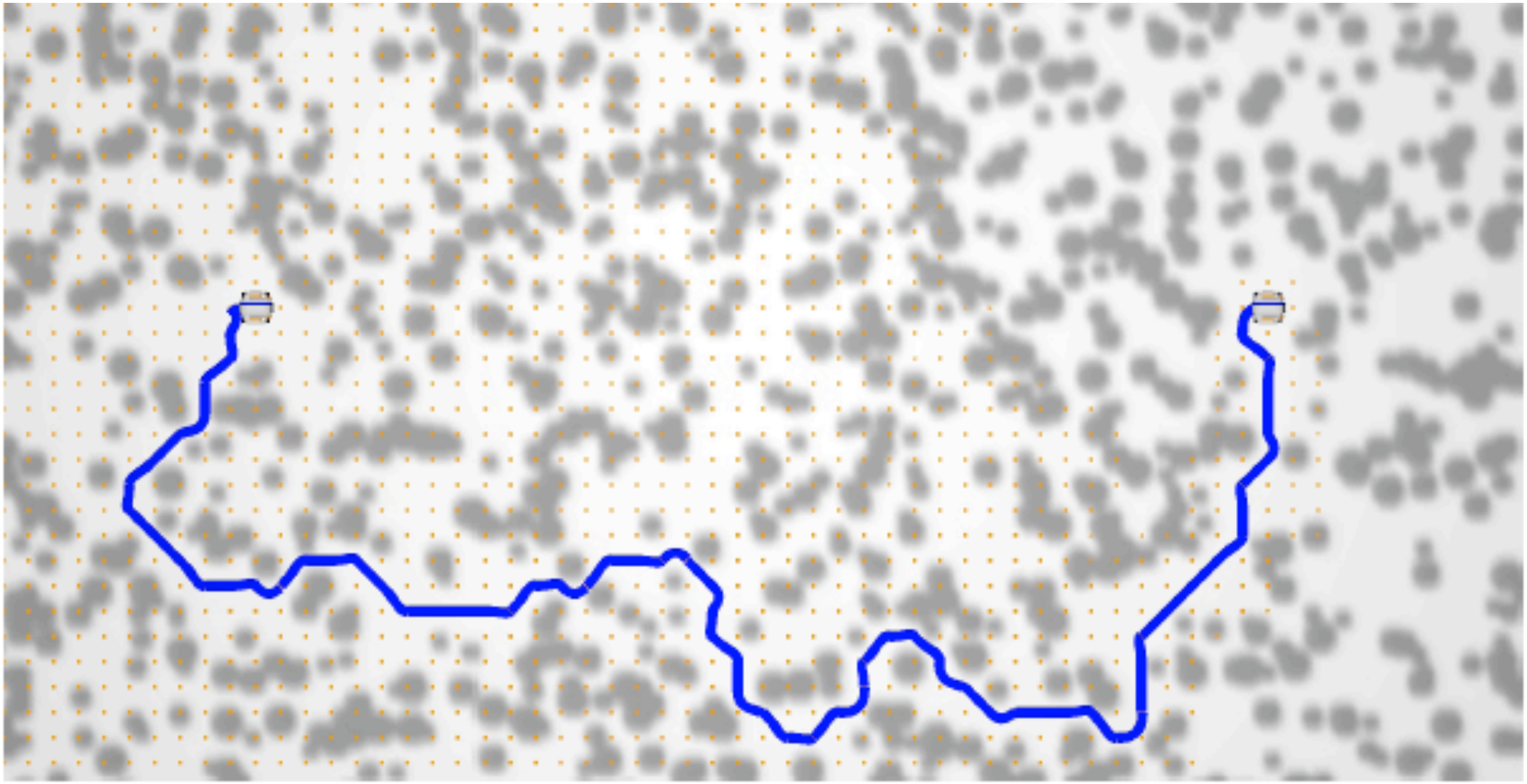
Syllabus: Spring Quarter: Motion Planning and Control



Search Spaces

Figure 5.1 from T.M. Howard: Adaptive Model-Predictive Motion Planning for Navigation in Complex Environments (2009)

Syllabus: Spring Quarter: Motion Planning and Control (cont.)



Costing and Search Algorithms

Figure 5.12a from T.M. Howard: Adaptive Model-Predictive Motion Planning for Navigation in Complex Environments (2009)

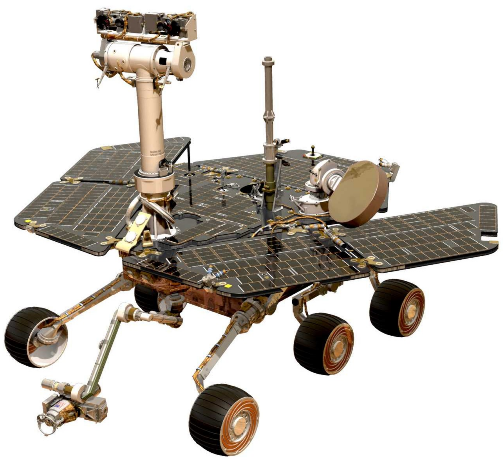
Syllabus: Spring Quarter: Motion Planning and Control (cont.)

Real-Time Mobile Robot Navigation

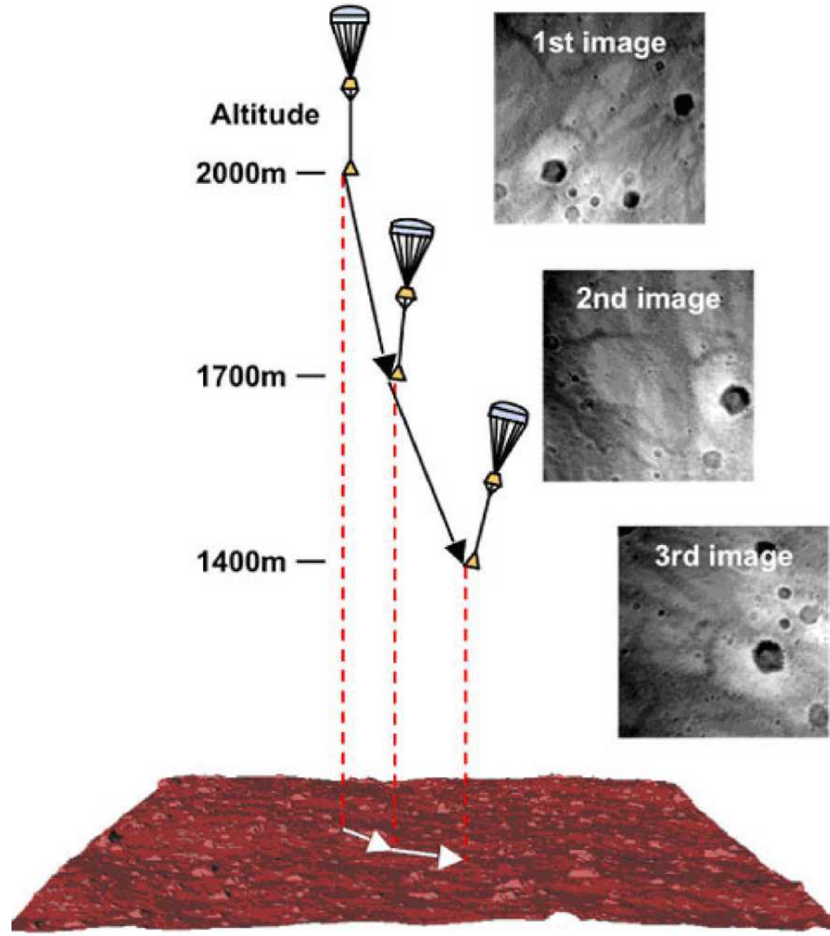
Figure 4.11 from T.M. Howard: Adaptive Model-Predictive Motion Planning for Navigation in Complex Environments (2009)

Spring Quarter Case Studies: Autonomous Navigation for Mars

Rover driving and localization



Safe and precise landing



Spring Quarter Project Possibilities

With Pioneer(s):

- Obstacle avoidance, mapping, path planning, and place recognition
- Follow-the-leader
- Moving object tracking and avoidance
- Basic robot team behaviors

With micro air vehicles:

- Vision-based state estimation, mapping, basic motion planning, and place recognition
- More complex things subject to ability

Next

- Lecture 2: illumination and radiometry
  - Read Szeliski sec. 2.2 (short); optionally read Szeliski ch. 1
  - Get started reading Szeliski sec. 2.1
- Lecture 3: cameras
  - Read Szeliski sec. 2.3
  - Read Forsyth ch. 1

Questions?