Sensors & Navigation

Joseph T. Wunderlich, Ph.D.

Early Navigation and Mapping

Christopher Columbus

Image from: http://www.christopher-columbus.eu/navigation.htm

Early Navigation and Mapping

Christopher Columbus's map

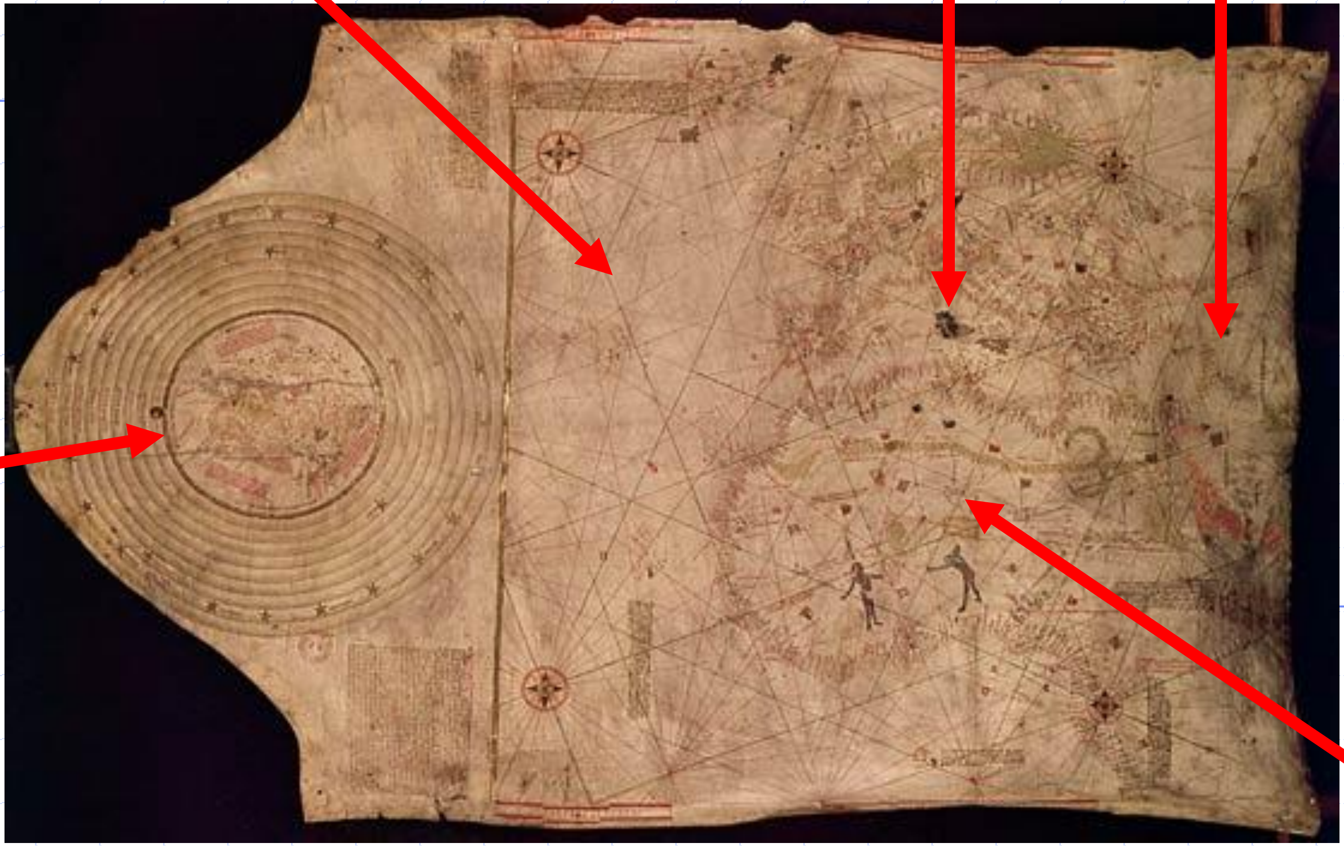


Image from: http://uk.encarta.msn.com/media_941583173/navigation_map_of_christopher_columbus.html

Early Navigation and Mapping

Columbus used
Dead Reckoning
(DR)
and
Celestial Navigation

Image from: http://www.christopher-columbus.eu/navigation.htm

Early Navigation and Mapping

Dead Reckoning (DR) Navigation

Navigator finds position by measuring **heading,** and **time** traveled; then calculates **distance** traveled and plots it along measured **heading** on a map. **Heading** measured with compass.

distance = **speed** x **time**

where **speed** calculated by throwing debris into water and measuring **time** for debris to float a fixed **length** between two marks on ship's side.

speed = **length** / **time**

Speed and **heading** were measured every hour.

Information and Image from: http://www.christopher-columbus.eu/navigation.htm

Early Navigation and Mapping

Celestial Navigation

EXAMPLE: **Using Astrolabe at night to find Latitude:**

- Step 1: Locate Polaris ("North Star"). This is only possible in Northern Hemisphere *Polaris is the only star that doesn't move across sky at night since Earth's axis of rotation points directly at it*

- Step 2: Hold up astrolabe and align it to Polaris and horizon; take a reading on how many degrees Polaris is above horizon

- Step 3: Subtract that number from 90 to get approximate latitude of where you at

Columbus with an Astrolabe

Image from: http://www.kofcmuseum.org/km/en/permanent/columbus/index.html

Image from: http://www.christopher-columbus.eu/navigation.htm

Example from: http://www.answerbag.com/articles/How-to-Use-an-Astrolabe/b237f220-175d-4dfd-649a-151c2fdbb1cb

Early Navigation and Mapping

Celestial Navigation

Polaris is only star that doesn't move across sky at night since Earth's axis of rotation points directly at it

Columbus with an Astrolabe

Go to Google Earth to see the night sky:
http://earth.google.com/
(click on the planet icon)

Image from: http://www.kofcmuseum.org/km/en/permanent/columbus/index.html

Image from: http://www.christopher-columbus.eu/navigation.htm

Sky Image from: http://www.astronomy.org/programs/seasons/index.html

Navigation and Sensors

Table 4.1
Classification of sensors used in mobile robotics applications

General classification (typical use)	Sensor Sensor System	PC or EC	A or P
(1) Tactile sensors (detection of physical contact or closeness; security switches)	Contact switches, bumpers Optical barriers Noncontact proximity sensors	EC EC EC	P A A
(2) Wheel/motor sensors (wheel/motor speed and position)	Brush encoders Potentiometers Synchros, resolvers Optical encoders Magnetic encoders Inductive encoders Capacitive encoders	PC PC PC PC PC PC PC	P P A A A A A
(3) Heading sensors (orientation of the robot in relation to a fixed reference frame)	Compass Gyroscopes (A MUST FOR UAV's) Inclinometers	EC PC EC	P P A/P
(4) Ground-based beacons (localization in a fixed reference frame)	GPS Active optical or RF beacons Active ultrasonic beacons Reflective beacons	EC EC EC EC	A A A A
(5) Active ranging (reflectivity, time-of-flight, and geometric triangulation) VS.	Reflectivity sensors Ultrasonic sensor Laser rangefinder "LIDAR" "LADAR" Optical triangulation (1D) Structured light (2D)	EC EC EC EC EC	A A A A A
(6) Motion/speed sensors (speed relative to fixed or moving objects)	Doppler radar Doppler sound MORE ACCURATE THAN BY USING (2)	EC EC	A A
(7) Vision-based sensors (visual ranging, whole-image analysis, segmentation, object recognition)	CCD/CMOS camera(s) Visual ranging packages Object tracking packages	EC	P

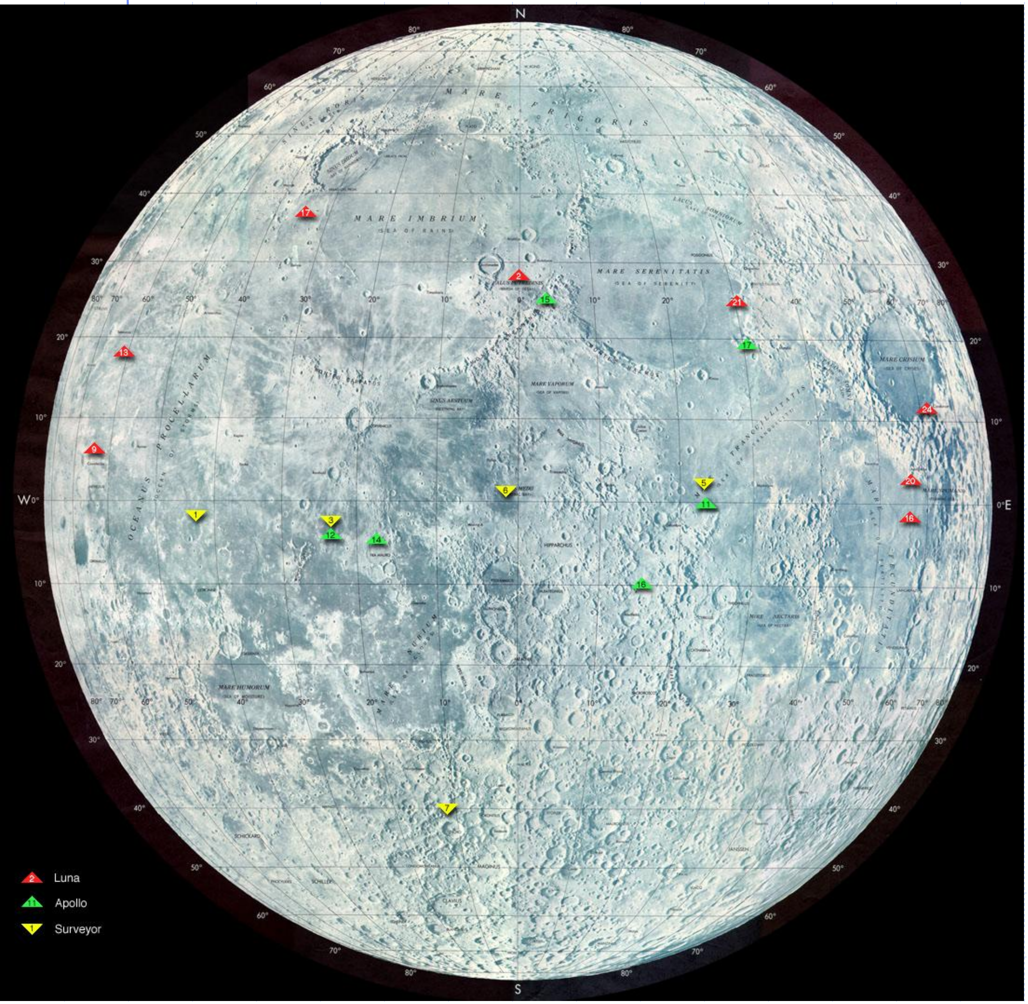
CAN TRIANGULATE WITH TWO CAMERAS

A, active; P, passive; P/A, passive/active; PC, proprioceptive; EC, exteroceptive.

SOURCE: R. Siegwart and I. Nourbakhsh, ***Autonomous mobile robots***, Massachusetts Institute of Technology, 2004.

Lunar Landings

Mapping



We often have much mapped GLOBALLY before we explore

(e.g., via telescope observations)

However we still need to get close to obtain **LOCAL details to improve GLOBAL MAP**

Image from: http://nssdc.gsfc.nasa.gov/planetary/planets/moonpage.html

Autonomous Navigation

- <u>1971</u>: NASA ***"Lunar Roving Vehicle"*** (LRV)

  Navigation designed to assist human operator with position, orientation, and shortest-path-to-Lander

  AUTONOMY: None needed – astronauts available

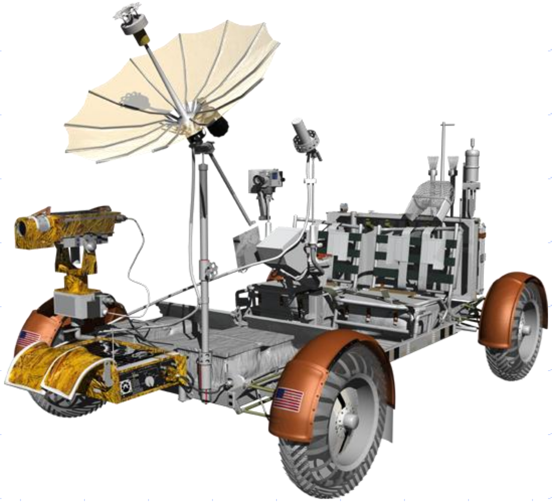


Image from: Young, A.H. ***Lunar and planetary rovers: the wheels of Apollo and the quest for mars***, Springer; 1 edition, August 1, 2006.

"Lunar Roving Vehicle" (LRV) 1972

Navigation ***Inputs***

1. <u>Pitch & Roll</u>
measured for
travel distance
calculations
(and to maintain stability)

Image from: Young, A.H. ***Lunar and planetary rovers: the wheels of Apollo and the quest for mars***, Springer; 1 edition, August 1, 2006.

“Lunar Roving Vehicle” (LRV)

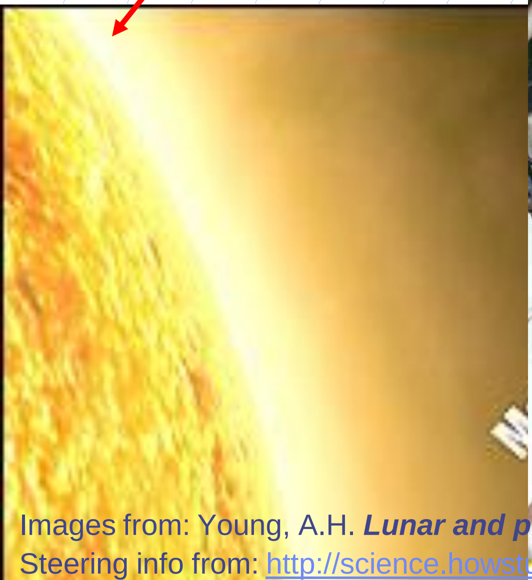
Navigation ***Inputs***

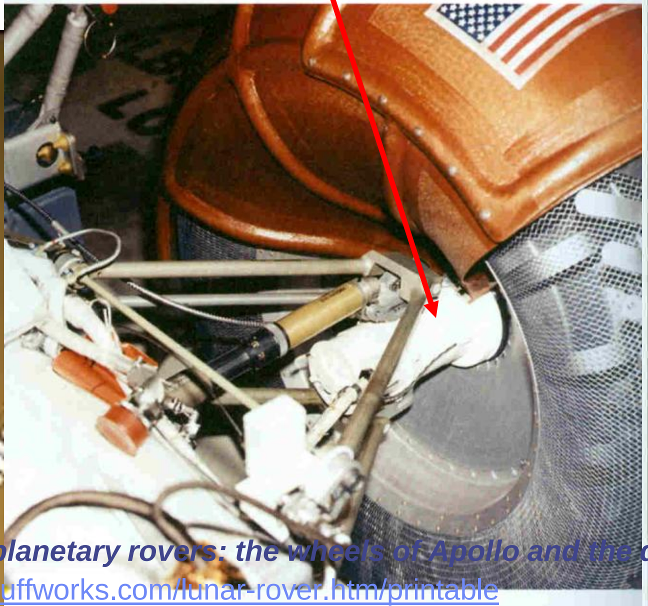
2. Motors have separate **odometers**
(since independently driven)

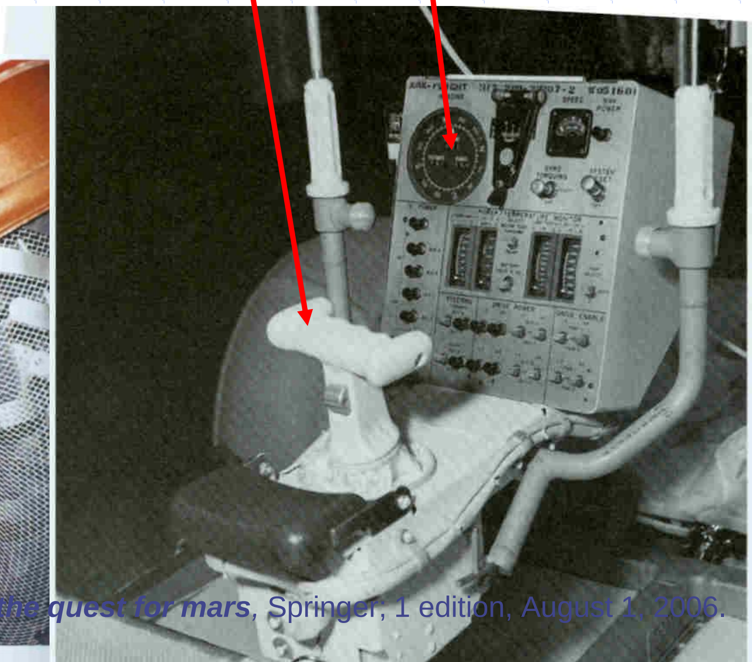
3. Angle of **sun** part of navigation inputs

4. **Steering** **(“T-Handle”)**
- Pivot forward = *accelerate forward*
- Pivot rearward = *accelerate backward*
- Pivot left = *turn left*
- Pivot right = *turn right*
- Slide handle backward = *apply the brake and disengage the throttle*
- Slide controller all the way back = *engage the parking brake*
- *Switch on handle activated reverse*

5. **Directional Gyro**







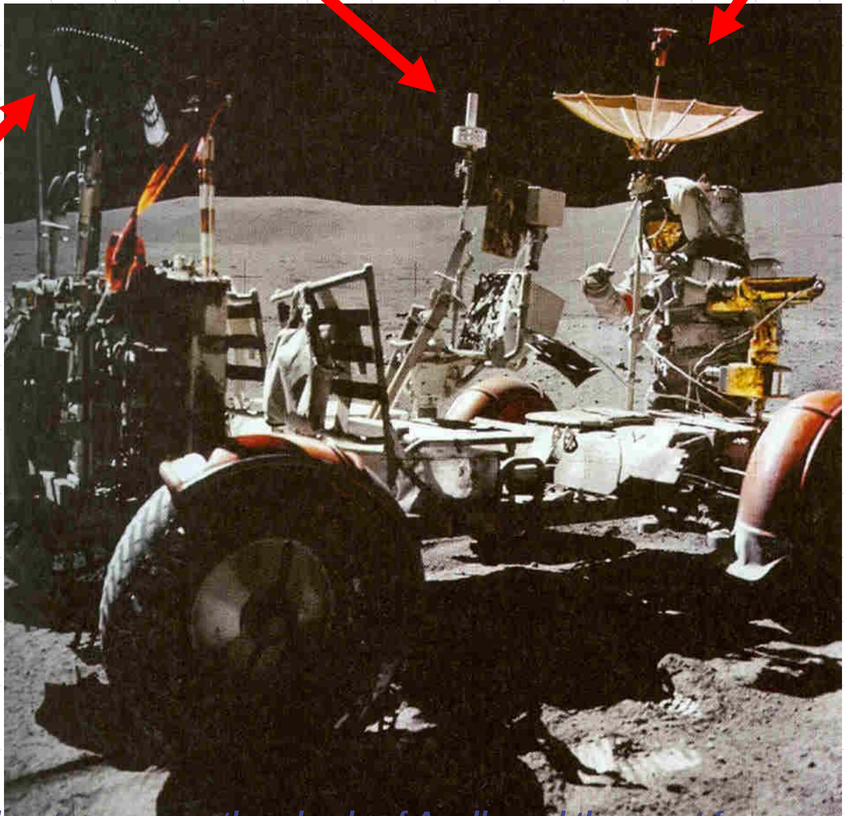
Images from: Young, A.H. ***Lunar and planetary rovers: the wheels of Apollo and the quest for mars***, Springer; 1 edition, August 1, 2006.
Steering info from: http://science.howstuffworks.com/lunar-rover.htm/printable

“*Lunar Roving Vehicle*” (LRV)

Navigation ***Inputs***

Low-Gain antenna for comm with Lunar Module (LM) lander

High-Gain antenna for direct comm with earth



Electrical Surface Properties Antenna also **not** part of navigation inputs

Communications **not** part of navigation since vehicle not tele-operated

Image from: Young, A.H. ***Lunar and planetary rovers: the wheels of Apollo and the quest for mars,*** Springer; 1 edition, August 1, 2006.

“Lunar Roving Vehicle” (LRV)

Boeing initially proposed an inertial guidance system that was rejected for not meeting NASA’s “**simplicity”** requirement

Inertial guidance systems combine accelerometers and gyros to track position and orientation in space (typically in planes and subs)

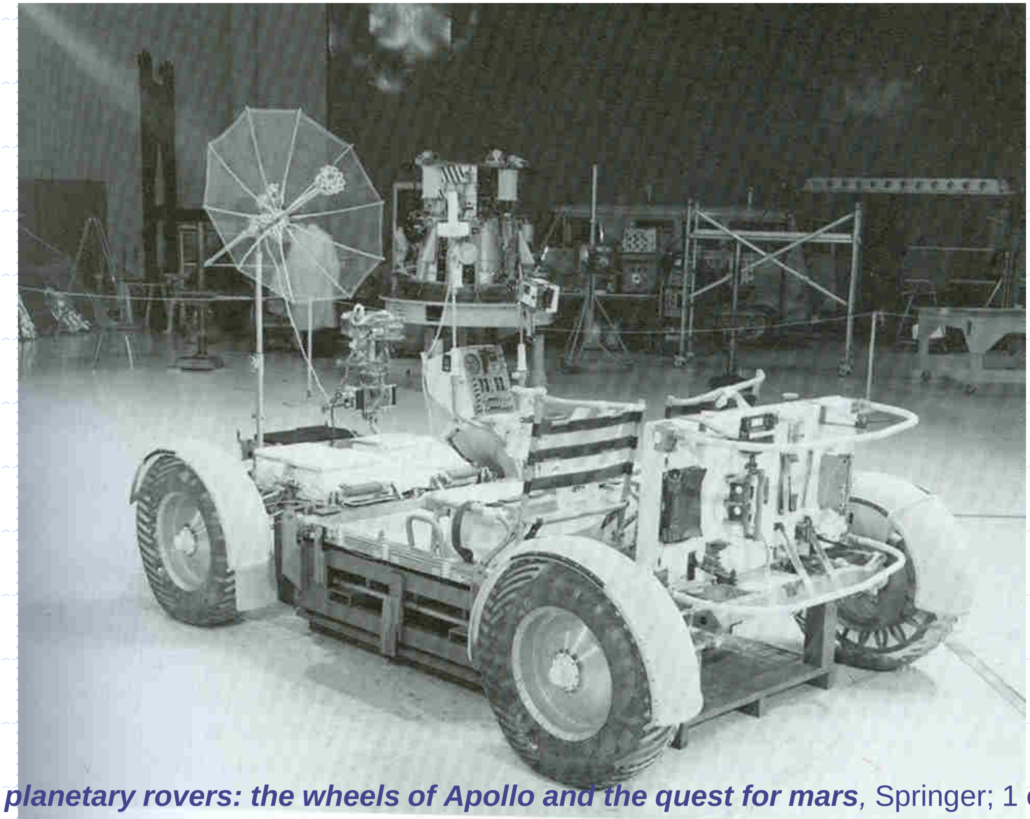
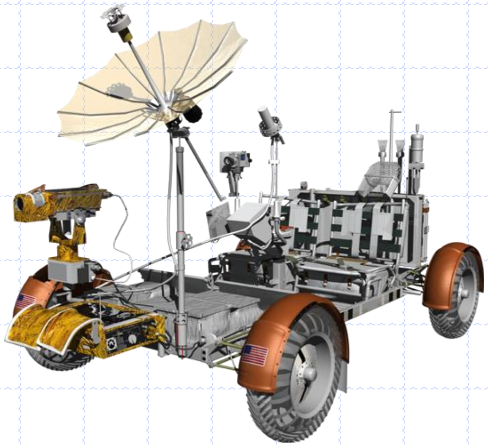


Image from: Young, A.H. ***Lunar and planetary rovers: the wheels of Apollo and the quest for mars***, Springer; 1 edition, August 1, 2006.

“Lunar Roving Vehicle” (LRV) *Navigation*

NASA requirements for all LRV subsystems:

1. **Simplicity**
2. **Reliability**
3. **Light weight**
4. **Ruggedness**
5. **Low power**



Additional requirements for Navigation subsystem:

1. Be relatively intuitive (to minimize crew familiarity training)
2. Retain navigation data in event of power interruption
3. Be manufactured using existing technology

Source: Young, A.H. ***Lunar and planetary rovers: the wheels of Apollo and the quest for mars***, Springer; 1 edition, August 1, 2006.

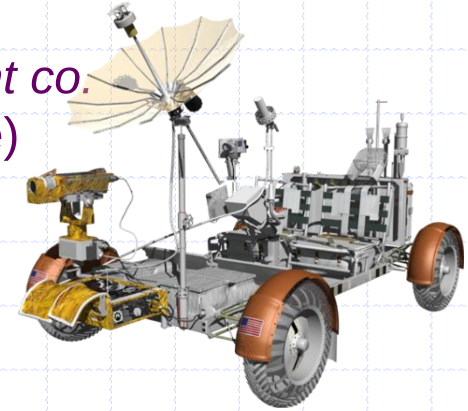
“Lunar Roving Vehicle” (LRV) *Navigation*

NASA functional specifications for LRV Navigation:

1. **Able to navigate to a predetermined location**
2. **Output speed and distance traveled**
3. **Calculate a <u>shortest path</u> back to Lander**

LRV Navigation subsystem components:

1. Directional Gyroscope Unit (DGU)*Lear Seigler Model 9010*
2. Sun angle measurement
3. Integrated Position Indicator (IPI) *by Abrams Instrument co.*
4. Four odometers (one for each independent wheel drive)
5. Custom Signal Processing Unit (SPU) by *Boeing co.*
   - This was the computer.



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“Lunar Roving Vehicle” (LRV) *Navigation*

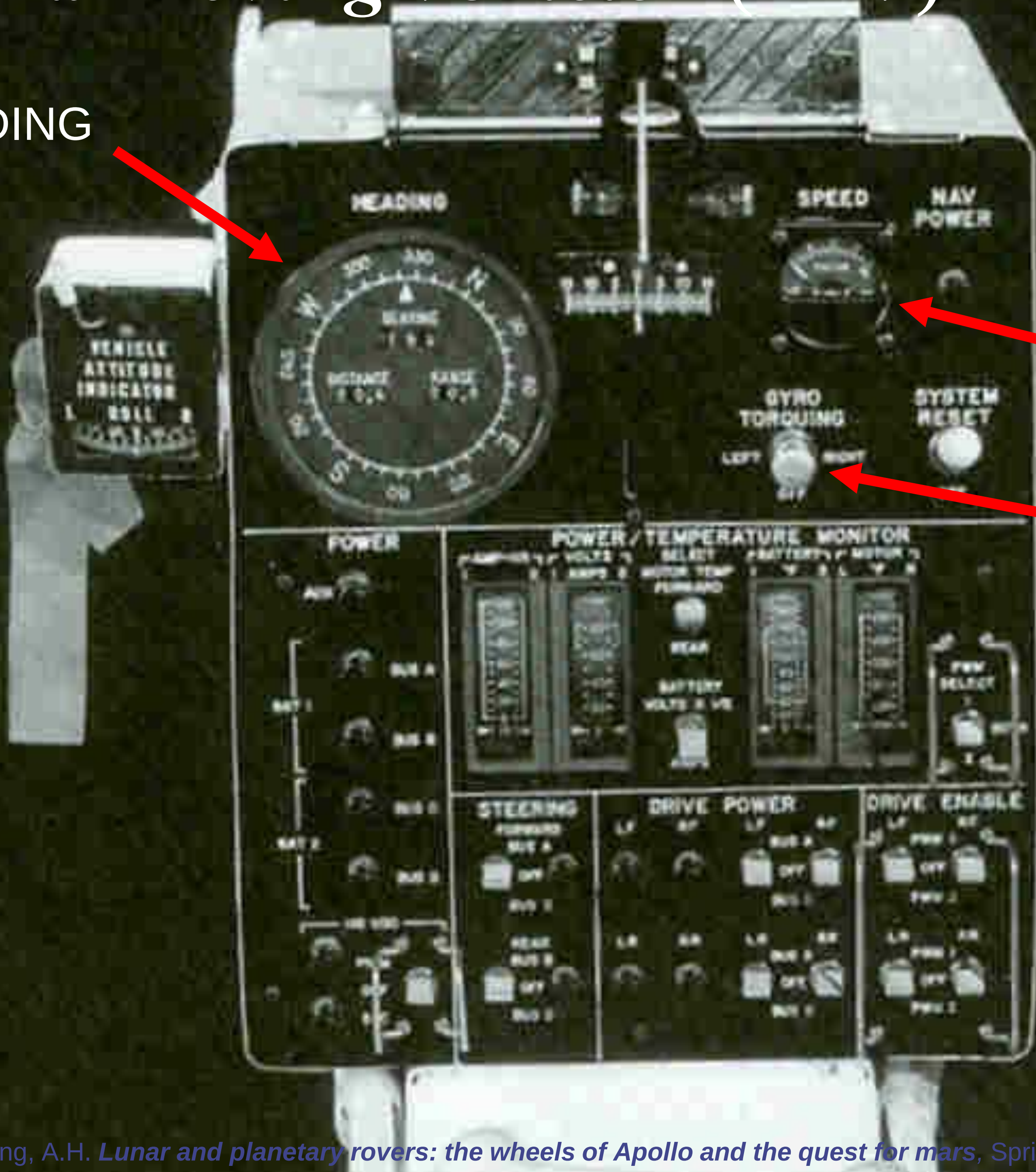


Image from: Young, A.H. ***Lunar and planetary rovers: the wheels of Apollo and the quest for mars***, Springer; 1 edition, August 1, 2006.

"Lunar Roving Vehicle" (LRV) *Navigation*

TESTING

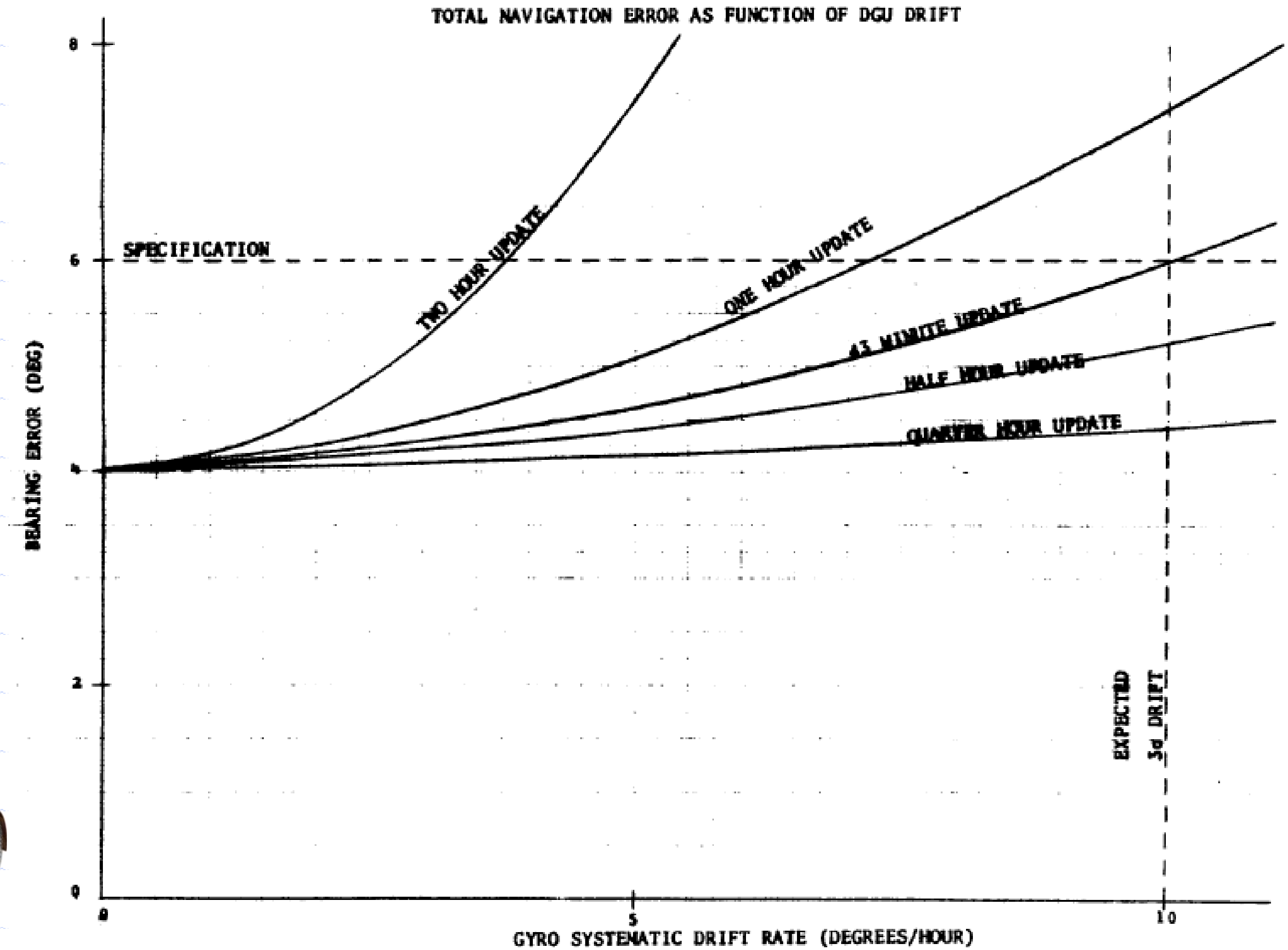
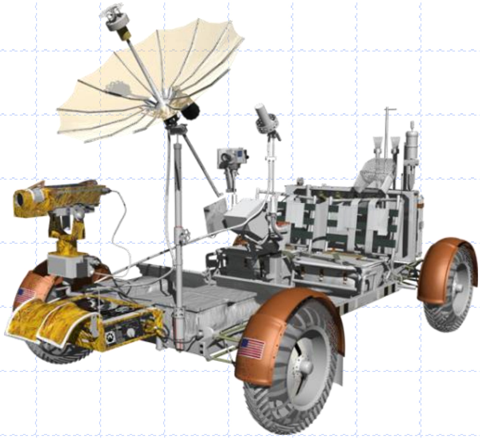


FIGURE 4-22 NAVIGATION BEARING ERROR AS A FUNCTION OF DGU DRIFT



SOURCE: Boeing Company and NASA (1971) **LRV operations handbook. appendix A performance data**. Document LS006-002-2H.

Image: Young, A.H. ***Lunar and planetary rovers: the wheels of Apollo and the quest for mars***, Springer; 1 edition, August 1, 2006.

Navigation and Mapping

Knowing position and orientation is essential in all navigation

Local path-planning (like dead-reckoning) does not guarantee optimal paths

Image from: http://www.christopher-columbus.eu/navigation.htm

Navigation and Mapping

Establishing a reference frame (like with Celestial Navigation) helps develope a Global path-planning scheme

Image from: http://www.christopher-columbus.eu/navigation.htm

Navigation and Mapping

Then optimal Global paths can be found using one or several optimization techniques

-- including global adaptation strategies to avoid known or discovered obstacles

Or use local obstacle avoidance techniques, followed by adaptive response of the Global Path-planner

Image from: http://www.christopher-columbus.eu/navigation.htm

LOCAL Navigation Example (Etown Students)

1) Define problem: The following problem was assigned to three groups of four students in the course: "*Simulation & Modeling Physical Systems*" at Elizabethtown College: [1]

"Program a real-time controlled mobile robot to seek a light source in a four-foot by four-foot pen. A one-foot by one-foot square obstacle is located at the center of the pen. When the robot finds the light, it should stop and play a song. Also, write a simulation of the mobile robot. The simulated robot, light, and environment should model the real physical system as closely as possible. The real-time control program code is to control a robot constructed from a "Lego Mindstorm" programmable "RCX" block (supplied by professor). The following programming languages must be used by each group to program the real-time controlled robot:

- *Group #1: Visual-Basic* [2]
- *Group #2: A variation of C ("Not Quite C")* [3,4]
- *Group #3: Standard RCX code* [5]

The location of the light, and the initial location and orientation of the robot must be chosen by mouse-click at the beginning of every simulation program run. The professor will select the light location and initial robot location and orientation for both your simulation and real-time robot demonstrations on the day of your presentation. Once all of the robots have been demonstrated to perform the above task, designate one of the robots to find the light, then search for the remaining two robots and notify them that the light has been found by sending an encoded message via IR communication; the remaining two robots will then acknowledge this message by playing a tune. The professor will select the light location and initial robot locations and orientations on the day of your presentation. A sketch of a robot, light-source, enclosure, and obstacle is shown in Fig. 1".

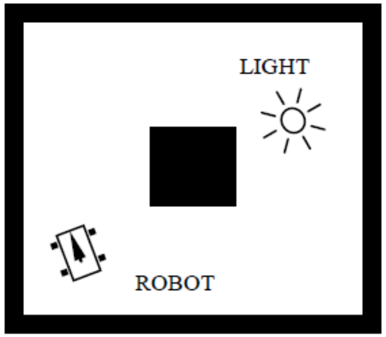


Figure 1. Sketch of a robot, light-source, enclosure, and obstacle.

FROM: Wunderlich, J.T. (2001). Simulation vs. real-time control; with applications to robotics and neural networks. In *Proceedings of 2001 ASEE Annual Conference & Exposition, Albuquerque, NM*: (session 2793), [CD-ROM]. ASEE Publications.

LOCAL
Navigation
Example
(Etown Students)

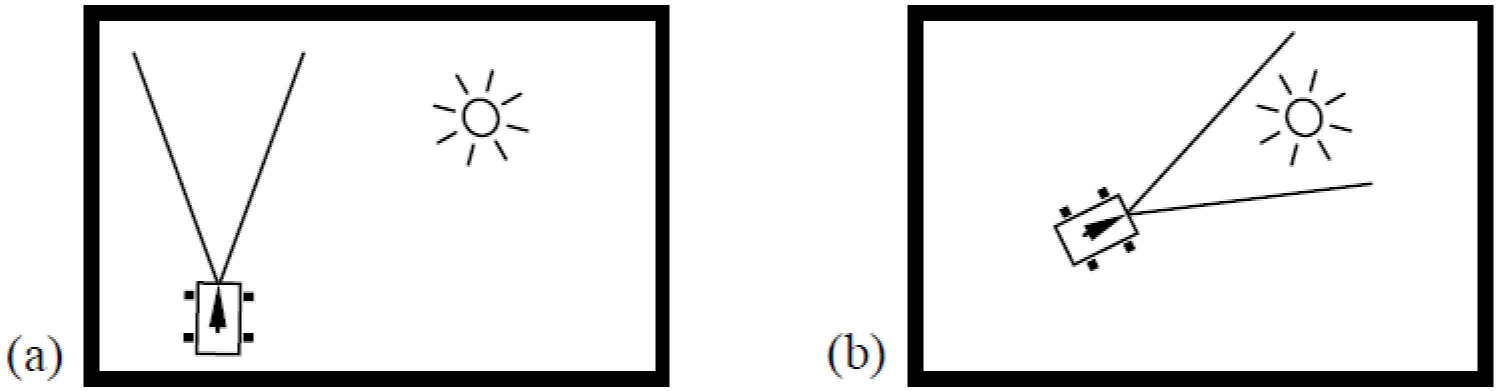


Figure 2. "Cone of vision" a) Light not within "cone" b) Light within "cone".

FROM: Wunderlich, J.T. (2001). Simulation vs. real-time control; with applications to robotics and neural networks. In *Proceedings of 2001 ASEE Annual Conference & Exposition, Albuquerque, NM*: (session 2793), [CD-ROM]. ASEE Publications.

LOCAL Navigation Example (Etown Students)

Mobile Robots move in continuous incremental steps in the direction of a **Unit Vector** which is defined by having a length of 1, and therefore it's x and y components should create a hypotenuse = 1

$$\vec{u} = \begin{bmatrix} \vec{u}_x \\ \vec{u}_y \end{bmatrix} = \begin{bmatrix} (x_{light} - x_{robot}) \big/ \sqrt{(x_{light} - x_{robot})^2 + (y_{light} - y_{robot})^2} \\ (y_{light} - y_{robot}) \big/ \sqrt{(x_{light} - x_{robot})^2 + (y_{light} - y_{robot})^2} \end{bmatrix}$$

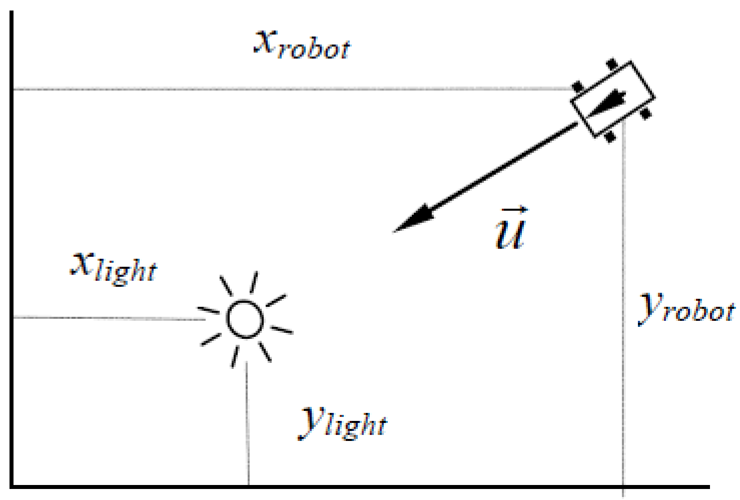


Figure 3. Unit vector defining direction from robot to light.

FROM: Wunderlich, J.T. (2001). Simulation vs. real-time control; with applications to robotics and neural networks. In *Proceedings of 2001 ASEE Annual Conference & Exposition, Albuquerque, NM*: (session 2793), [CD-ROM]. ASEE Publications.

LOCAL Navigation Example (Etown Students)

A Mobile Robot's **POSE** is defined by it's position and orientation within a reference frame

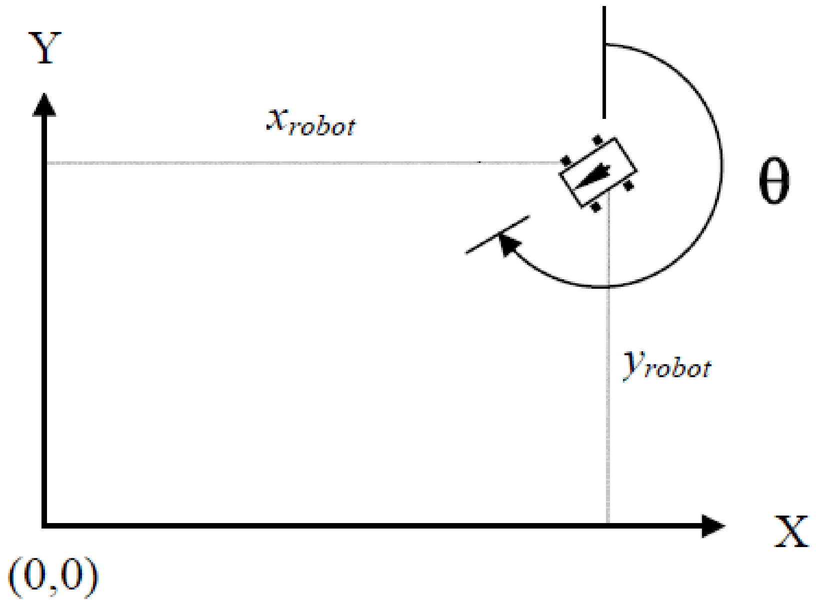
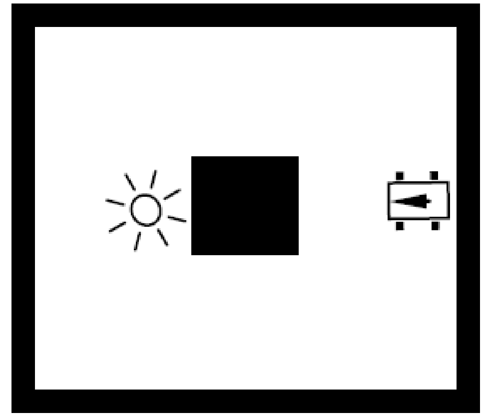


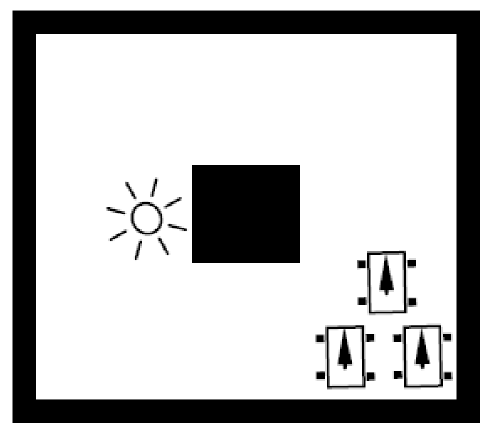
Figure 4. Some information needed for drawing robot graphics in simulation. (i.e., Coordinate system, robot position, and robot orientation).

FROM: Wunderlich, J.T. (2001). Simulation vs. real-time control; with applications to robotics and neural networks. In *Proceedings of 2001 ASEE Annual Conference & Exposition, Albuquerque, NM*: (session 2793), [CD-ROM]. ASEE Publications.

LOCAL
Navigation Example (Etown Students)



(a)



(b)

Figure 5. Light location and initial robot location(s) and orientation(s) defined by professor on day of demonstration. a) Single-robot task. b) Multi-robot task.

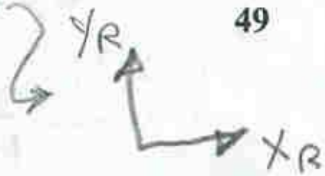
FROM: Wunderlich, J.T. (2001). Simulation vs. real-time control; with applications to robotics and neural networks. In *Proceedings of 2001 ASEE Annual Conference & Exposition, Albuquerque, NM*: (session 2793), [CD-ROM]. ASEE Publications.

GLOBAL Navigation Example (MIT Textbook)

SOURCE: R. Siegwart and I. Nourbakhsh, ***Autonomous mobile robots***, Massachusetts Institute of Technology, 2004.

GLOBAL REFERENCE FRAME:

LOCAL REFERENCE FRAME OF ROBOT R



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POSITION: P AT SOME POINT x, y IN GLOBAL FRAME $\{X_I, Y_I\}$

ORIENTATION: θ RELATIONSHIP BETWEEN FRAMES

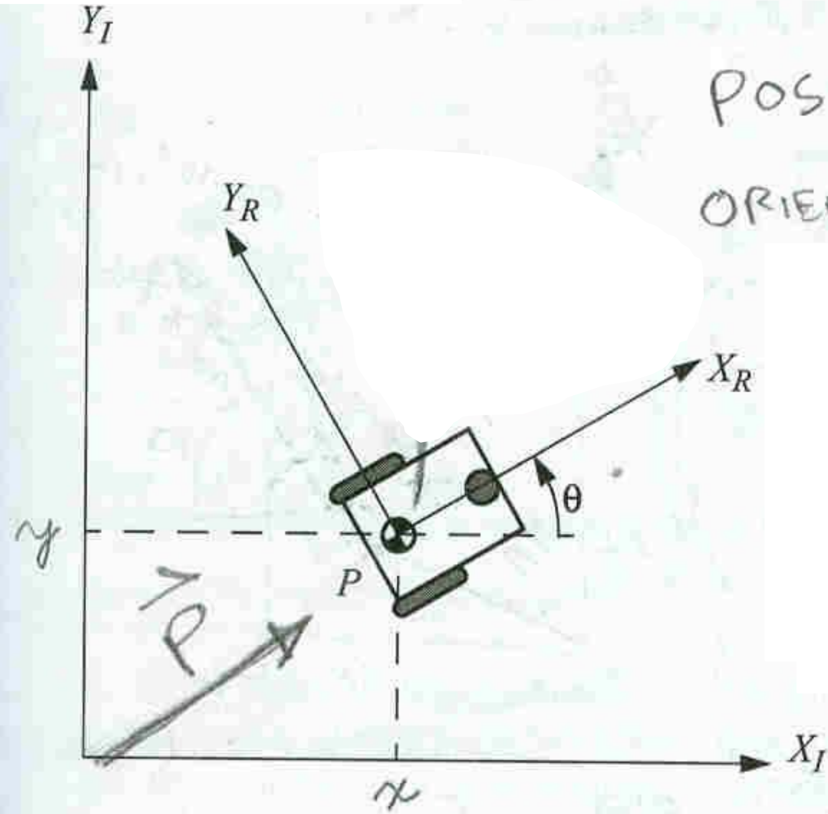


Figure 3.1
The global reference frame and the robot local reference frame.

"POSE"

$$\xi_I = \begin{bmatrix} x \\ y \\ \theta \end{bmatrix}$$

GLOBAL Navigation Example (MIT Textbook)

SOURCE: R. Siegwart and I. Nourbakhsh, ***Autonomous mobile robots***, Massachusetts Institute of Technology, 2004.

MAP FROM GLOBAL FRAME $\{X_I, Y_I\}$ TO LOCAL FRAME $\{X_R, Y_R\}$ USING

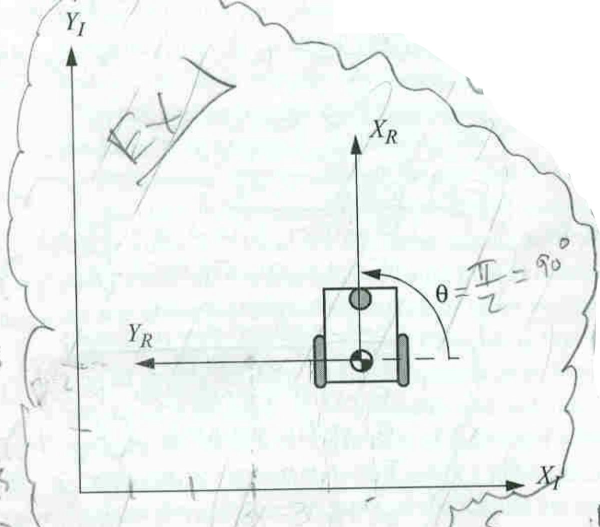


Figure 3.2
The mobile robot aligned with a global axis.

$$\xi_R = R(\theta) * \xi_I$$

WHERE:

ORTHOGANAL PROJECTION MATRIX

$$R(\theta) = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\underbrace{\begin{bmatrix} x_R \\ y_R \\ \theta_R \end{bmatrix}}_{\xi_R} = \underbrace{\begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{R(\theta)} \underbrace{\begin{bmatrix} x \\ y \\ \theta \end{bmatrix}}_{\xi_I}$$

$x_R = x(\cos\theta) + y(\sin\theta) + \theta(0)$
$y_R = x(-\sin\theta) + y(\cos\theta) + \theta(0)$
$\theta_R = x(0) + y(0) + \theta(1) = \theta$

This matrix can be used to map motion in the global reference frame $\{X_I, Y_I\}$ to motion in terms of the local reference frame $\{X_R, Y_R\}$. This operation is denoted by $R(\theta)\dot{\xi}_I$ because the computation of this operation depends on the value of θ:

For example, consider the robot in figure 3.2. For this robot, because $\theta = \frac{\pi}{2}$ we easily compute the instantaneous rotation matrix R:

$$R(\frac{\pi}{2}) = \begin{bmatrix} 0 & 1 & 0 \\ -1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Given some velocity ($\dot{x}, \dot{y}, \dot{\theta}$) in the global reference frame we can compute the components of motion along this robot's local axes X_R and Y_R. In this case, due to the specific angle of the robot, motion along X_R is equal to $\dot{y}$ and motion along Y_R is $-\dot{x}$:

$$\dot{\xi}_R = R(\frac{\pi}{2})\dot{\xi}_I = \begin{bmatrix} 0 & 1 & 0 \\ -1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \dot{y} \\ -\dot{x} \\ \dot{\theta} \end{bmatrix}$$

GLOBAL Navigation Example (MIT Textbook **+ Bunny)**

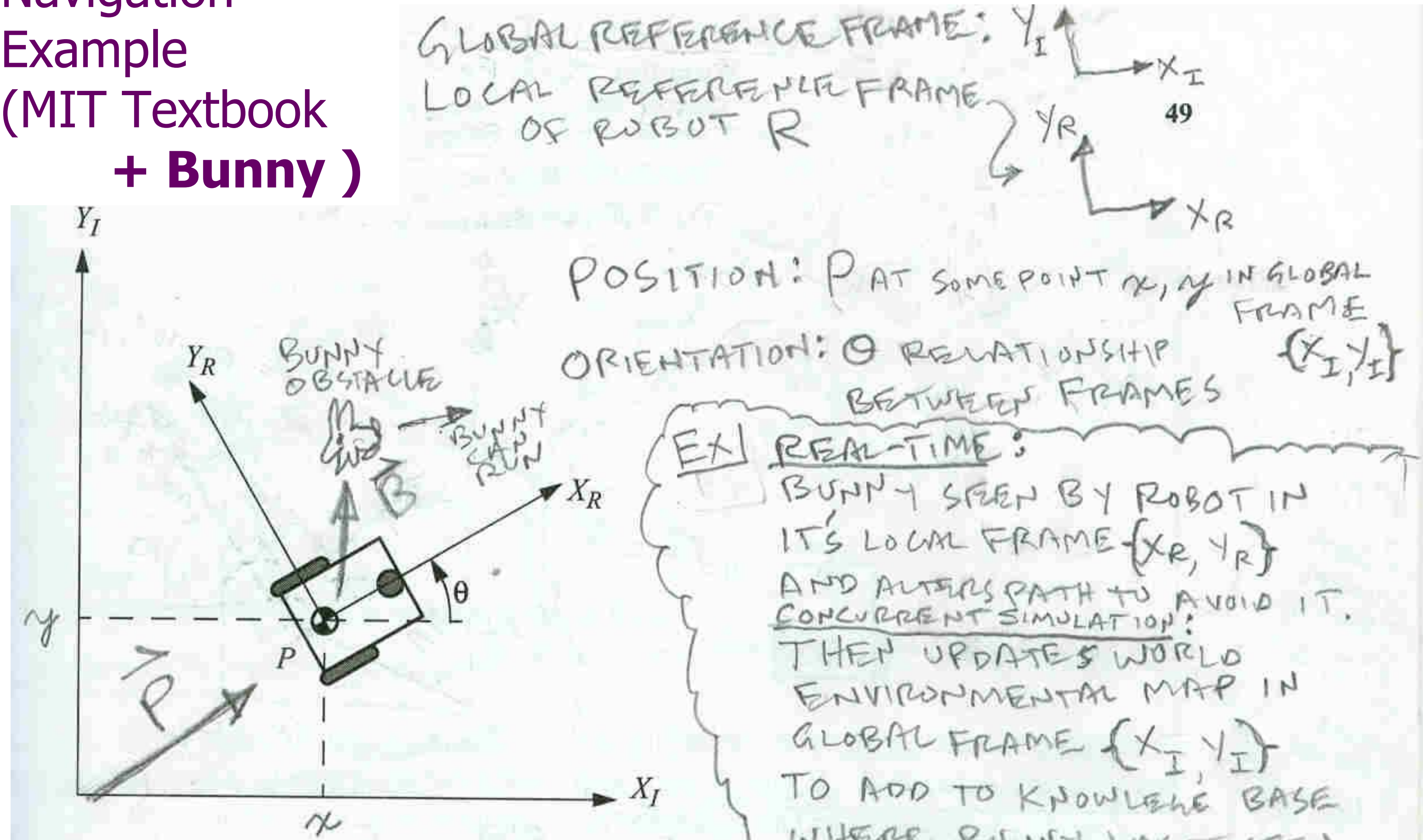


Figure 3.1
The global reference frame and the robot local reference frame.

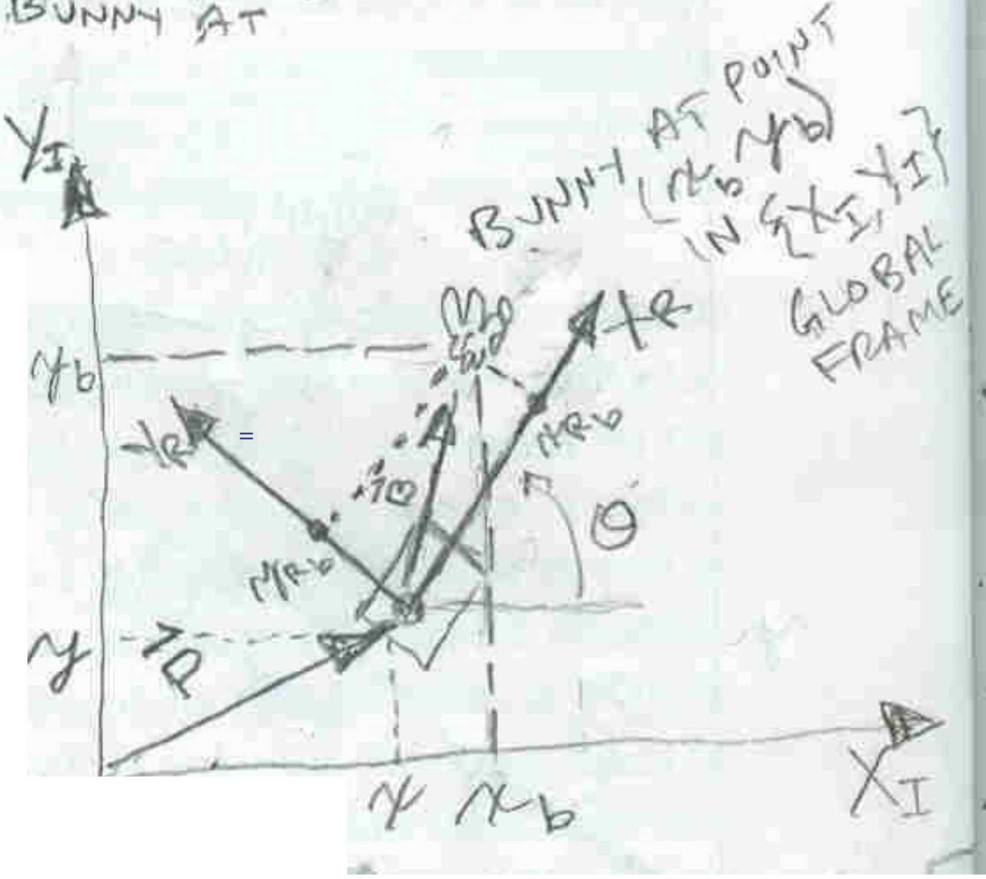
SOURCE: R. Siegwart and I. Nourbakhsh, ***Autonomous mobile robots***, Massachusetts Institute of Technology, 2004.

GLOBAL Navigation Example (MIT Textbook **+ Bunny)**

<u>CONCURRENT SIMULATION:</u>

PREDICTS A POINT x_b, y_b IN GLOBAL FRAME $\{X_I, Y_I\}$ WHERE BUNNY IS EXPECTED TO BE.

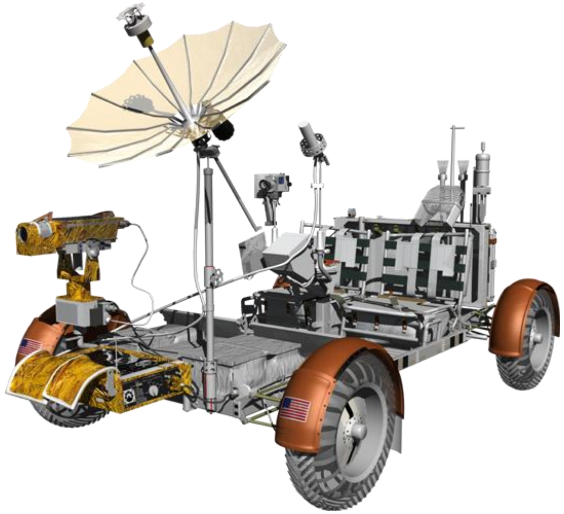
THEN TELLS <u>REAL-TIME</u> PATH-PLANNER WHAT COORDINATES (x_{R_b}, y_{R_b}) IN LOCAL FRAME $\{X_R, Y_R\}$ TO EXPECT BUNNY AT



SOURCE: R. Siegwart and I. Nourbakhsh, ***Autonomous mobile robots***, Massachusetts Institute of Technology, 2004.

Manned vs. Unmanned

Manned missions require less equipment for navigation since human in the loop



Tele-robotic systems in close proximity to human operator require little to no autonomous decision making
*(i.e., like **R**emote **C**ontrolled toys)*

Image from: Young, A.H. ***Lunar and planetary rovers: the wheels of Apollo and the quest for mars***, Springer; 1 edition, August 1, 2006.
Image from: http://siyuan0755.en.made-in-china.com/product/gqSEnvYOCLWM/China-RC-Car-with-Security-Infrared-Camera.html

Manned vs. Unmanned

Navigation in unmanned systems becomes more complex if system must respond autonomously to some or all situations

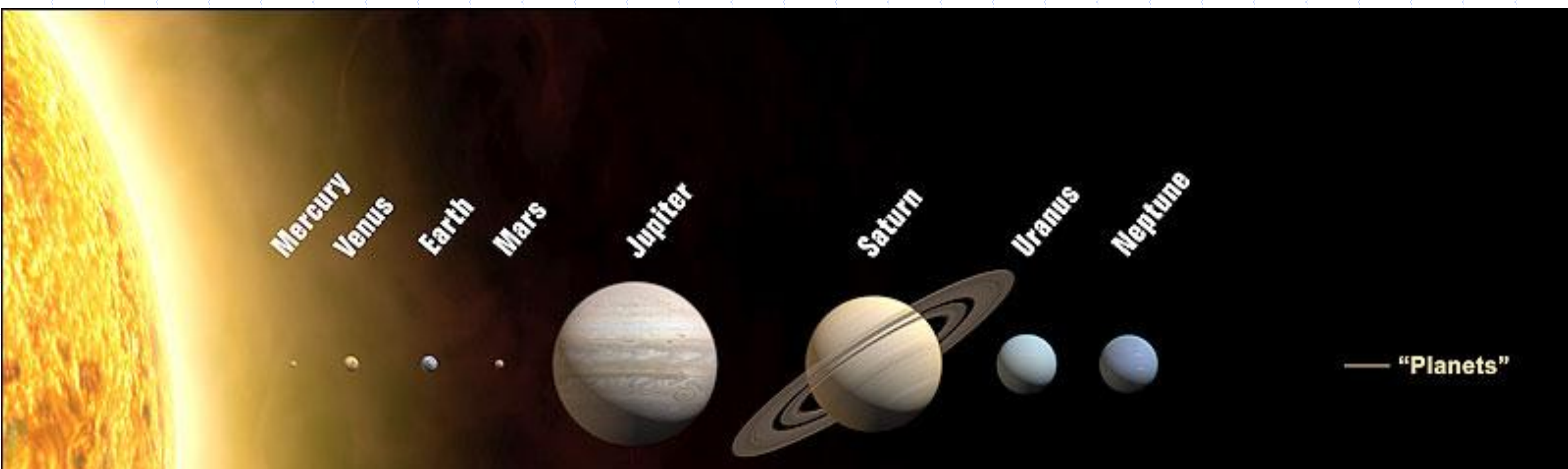


Image from http://www.punahou.edu/acad/sanders/geometrypages/GP14Astronomy.html

Manned vs. Unmanned

Tele-robotic systems at great distances (e.g., Mars) must either move very slowly, "blindly," or in a "broad-command sense" (i.e., executing a sol's worth of commands stored from Earth) since it takes up to ~25 minutes for signals to reach Mars

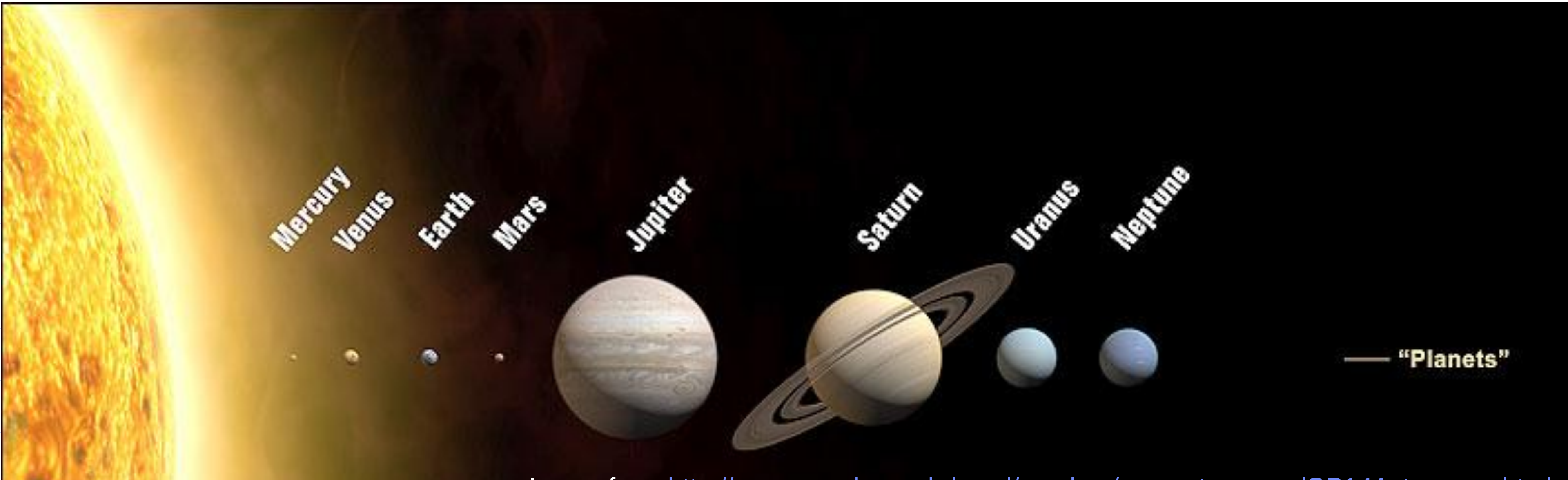


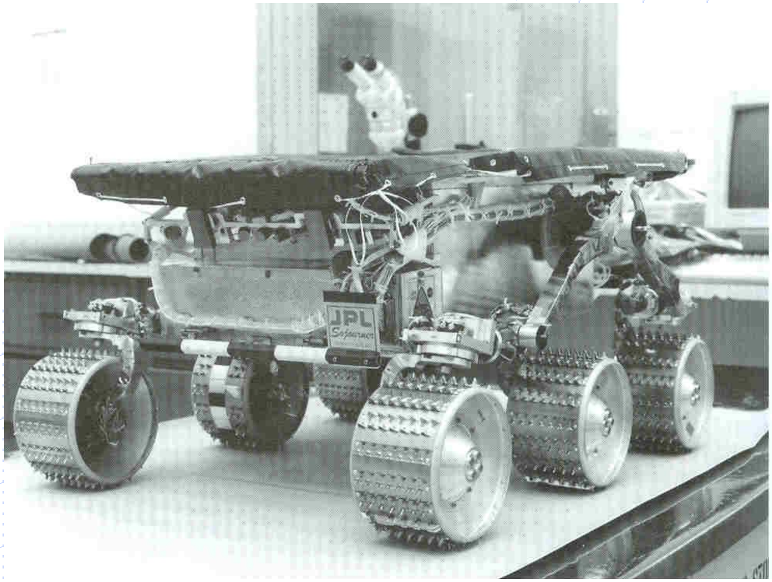
Image from http://www.punahou.edu/acad/sanders/geometrypages/GP14Astronomy.html

Autonomous Navigation

- 1996: NASA Pathfinder ***"Sojourner"***

Stereo cameras and five infrared laser stripes to detect hazards. Sensed 20 3D points per navigation step

AUTONOMY:
- Terrain Navigation
- Contingency Response
- Resource Management
- "Find Rock" COMMAND
- "Thread Needle" COMMAND



SOURCE: Bajracharya, M., Maimone, M.W., and Helmick, D. (2008). **Autonomy for mars rovers: past, present, and future**. In *Computer*: December, 2008. (pp. 44-50). *IEEE Press. (available at http://marstech.jpl.nasa.gov/publications/z02_0102.pdf)*

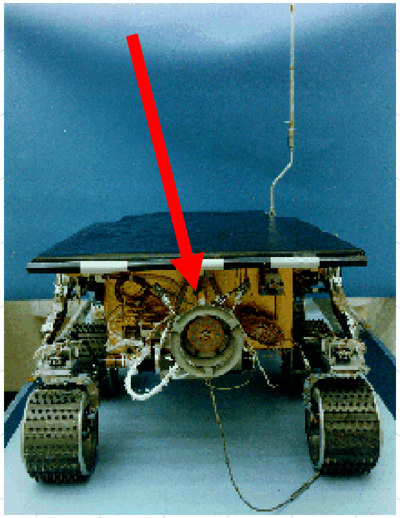
Image from: Young, A.H. ***Lunar and planetary rovers: the wheels of Apollo and the quest for mars***, Springer; 1 edition, August 1, 2006.

Mars Pathfinder "Sojourner"

1990's

Sensors for scientific data
(not used in Navigation)

Alpha Proton X-Ray Spectrometer



Atmospheric Structure Instrument/Meteorology Package

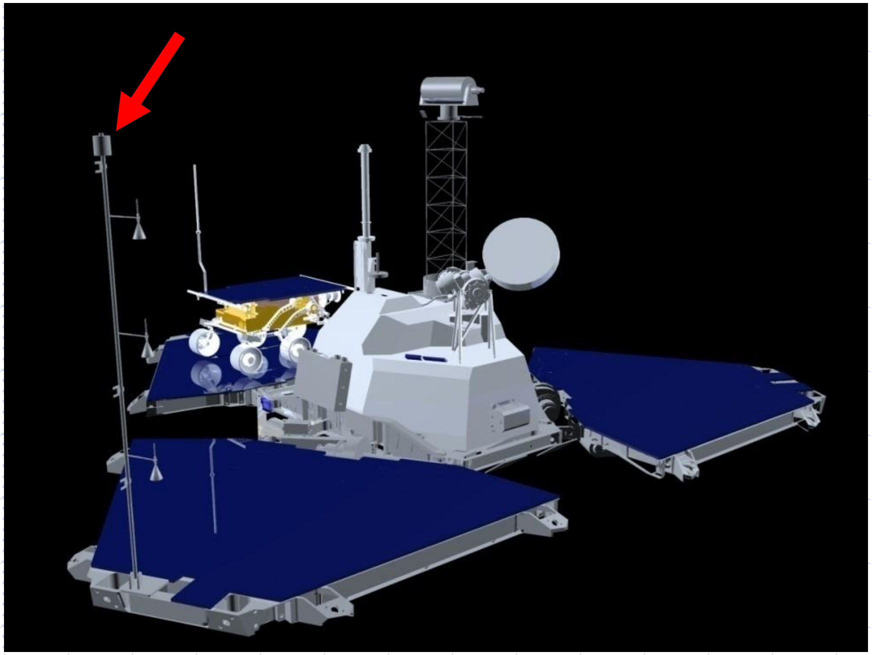


Image from: http://marsprogram.jpl.nasa.gov/MPF/mpf/sci_desc.html
Image from: http://starbase.jpl.nasa.gov/mpfl-m-asimet-3-rdr-surf-v1.0/mpam_0001/document/asmtinst.htm

Mars Rovers

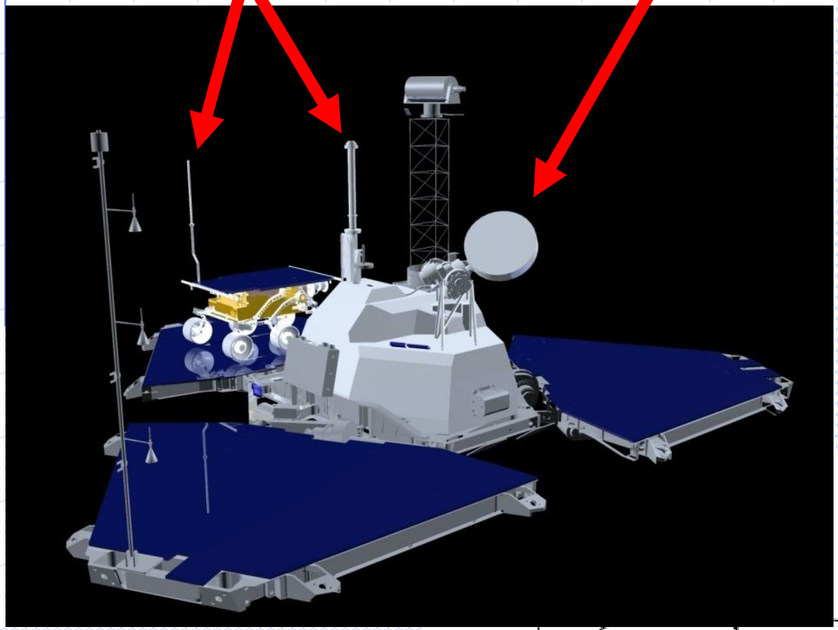
Navigation and Sensors

1990's

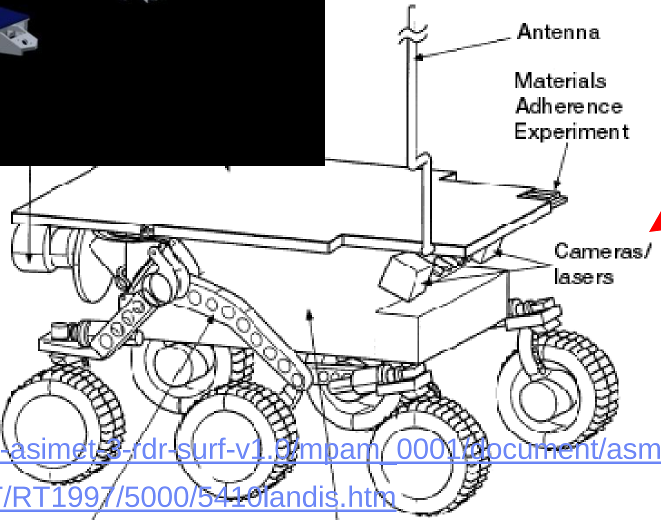
Mars Pathfinder "Sojourner"

Low-gain antennae for comm between rover and lander

High-gain antenna for comm with Earth



Since Sojourner mostly tele-operated from earth, **communication was part of rover's navigation**



Cameras and lasers used for obstacle avoidance

Image from: http://starbase.jpl.nasa.gov/mpfl-m-asimet-3-rdr-surf-v1.0/mpam_0001/document/asmtinst.htm

Image from: http://www.grc.nasa.gov/WWW/RT/RT1997/5000/5410landis.htm

Autonomous Navigation

- 2004: NASA Mars Explorer Rovers "***Spirit" and "Opportunity"***

Image processing to sense 15,000 to 40,000 3D points per image

AUTONOMY:
- Terrain Navigation while avoiding geometric hazards
- Visual pose estimation
    = *f* (wheel rotation, accelerometer, and angular velocity)
- Absolute orientation sensing
    = *f* (sun angle and gravity)
- 2006 UPGRADES UPLOADED:
    1. **GLOBAL path planner**
    2. Visual target tracking
    3. On-board dust devil and cloud detection
    4. Auto approach & place instrument

SOURCE: Bajracharya, M., Maimone, M.W., and Helmick, D. (2008). Autonomy for mars rovers: past, present, and future. In *Computer*: December, 2008. (pp. 44-50). *IEEE Press. (available at http://marstech.jpl.nasa.gov/publications/z02_0102.pdf)*

SOURCE: Carsen, A., Rankin, J., Fuguson, D., Stentz, A. (2007). Global path planning on board the Mars Exploration Rovers. In *Proceedings of the IEEE Aerospace Conference, 2007*. IEEE Press.

Image from: Young, A.H. ***Lunar and planetary rovers: the wheels of Apollo and the quest for mars***, Springer; 1 edition, August 1, 2006.

Mars Rovers

"Spirit" & "Opportunity"

Since still *somewhat* tele-operated from Earth, the communication system is still part of rover navigation

Cameras dedicated to Navigation

Other sensors for imaging

Other sensors for scientific data
(not used for Navigation)

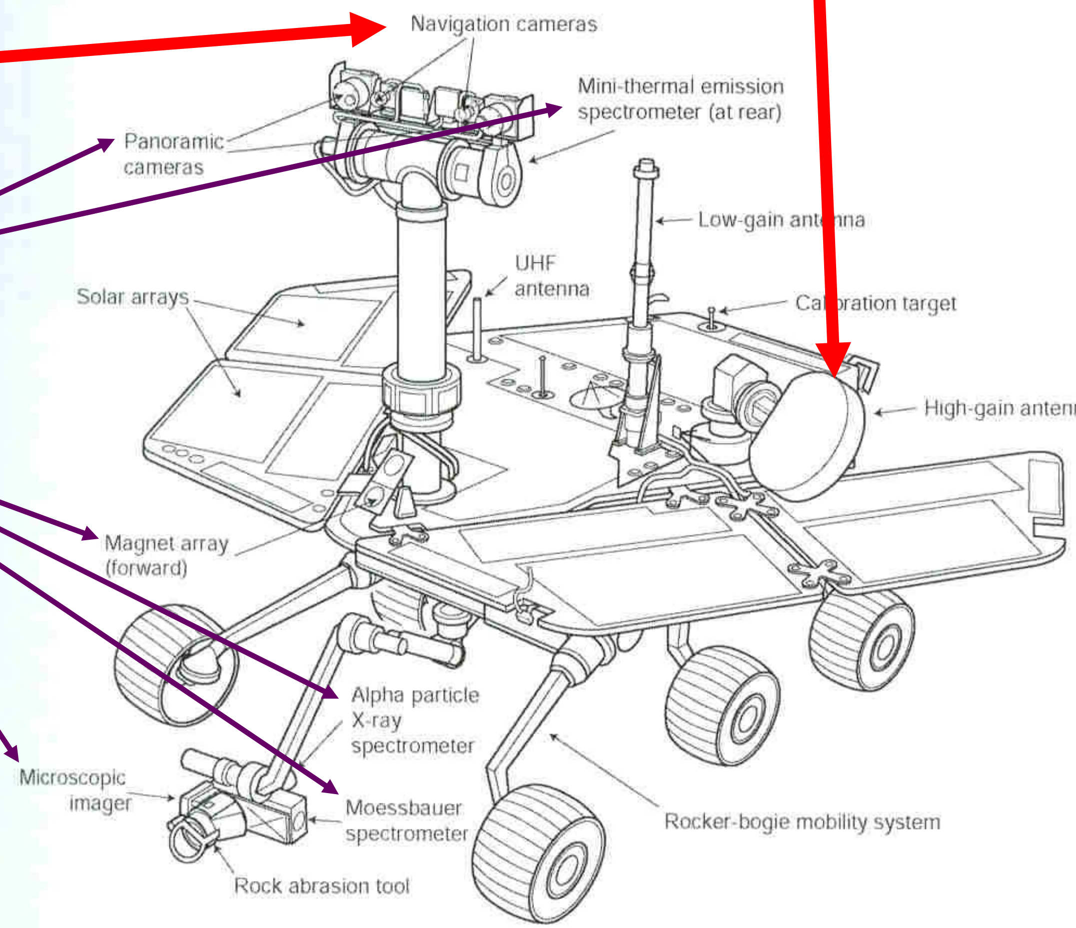


Image from: Young, A.H. ***Lunar and planetary rovers: the wheels of Apollo and the quest for mars***, Springer; 1 edition, August 1, 2006.

Mars Rovers

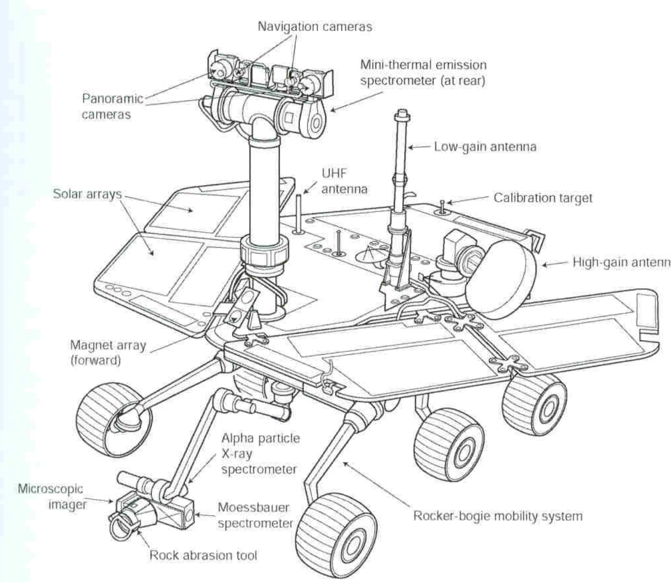
"Spirit" & "Opportunity"

Two methods to reach a goal:

1) **"Blind drive"**
   - Doesn't identify hazardous terrain; simply drives toward goal
   - Can cover a larger distance fast
   - Engineers on Earth verify terrain between rover and goal is free from hazards

2) **"AutoNav"** (**Auto**nomous **Nav**igation with hazard avoidance)
   - Identifies hazards and steers around
   - Slower, but keeps rover safe in regions unseen by engineers on Earth.

"Often, the two methods are utilized in tandem. First a blind drive is commanded as far out as engineers can be sure of safety. Then AutoNav used to make additional progress through unknown terrain."



SOURCE: Carsen, A., Rankin, J., Fuguson, D., Stentz, A. (2007). **Global path planning on board the Mars Exploration Rovers**. In *Proceedings of the IEEE Aerospace Conference, 2007*. IEEE Press.

Image from: Young, A.H. ***Lunar and planetary rovers: the wheels of Apollo and the quest for mars***, Springer; 1 edition, August 1, 2006.

Mars Rovers

"Spirit" & "Opportunity"

Navigation

2000's

AutoNav based on the **GESTALT** (**G**rid-based **E**stimation of **S**urface **T**raversability **A**pplied to **L**ocal **T**errain) which uses stereo image pairs to create a model of local terrain. Part of model is **goodness map**, an overhead grid view.

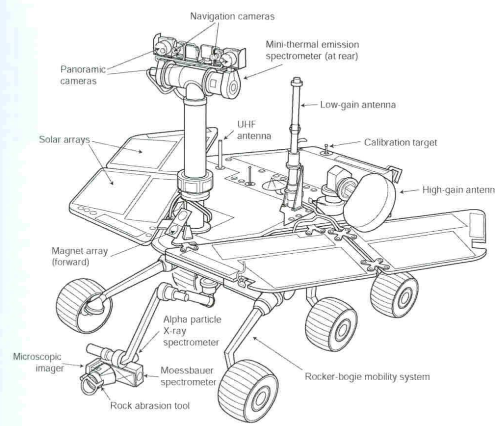
- Each grid contains a goodness value; high values indicate easily traversable terrain
- Map constructed in configuration space; meaning rover treated as a point

Once terrain evaluated, a set of candidate arcs is considered (with forward and backward arcs of varying curvature, as well as point turns to a variety of headings).

Each arc is evaluated on:

1. AVOIDING HAZARDS
2. MINIMIZING STEERING TIME
3. REACHING GOAL: Arcs that move rover closer to goal location receive higher "waypoint" votes

"Rover then drives a short predetermined distance along the selected arc . This process is repeated (evaluate terrain, select arc, drive) until the goal is reached, a prescribed Timeout period expires, or a fault is encountered"



SOURCE: Carsen, A., Rankin, J., Fuguson, D., Stentz, A. (2007). Global path planning on board the Mars Exploration Rovers. In *Proceedings of the IEEE Aerospace Conference, 2007*. IEEE Press.

Image from: Young, A.H. ***Lunar and planetary rovers: the wheels of Apollo and the quest for mars***, Springer; 1 edition, August 1, 2006.

Mars Rovers

"Spirit" & "Opportunity"

Navigation and Sensors

2006

***"Auto**nomous **Nav**igation with hazard avoidance (**<u>AutoNav</u>**) … works well to guide rovers around narrow and isolated hazards, however, susceptible to failure when clusters of closely spaced, non-traversable rocks form extended obstacles..... **<u>Field D*</u> GLOBAL** path planner **uploaded to in 2006** enables simultaneous local and global planning during AutoNav.*

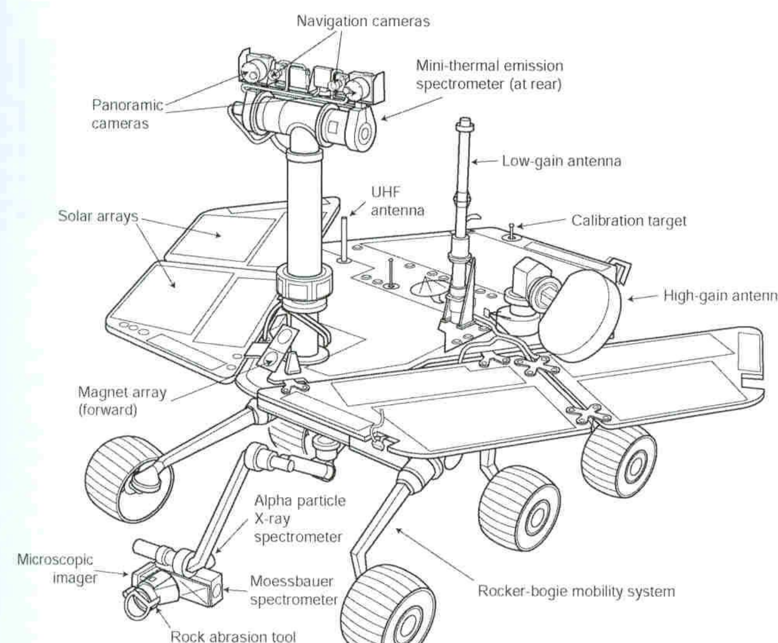


Image from: Young, A.H. ***Lunar and planetary rovers: the wheels of Apollo and the quest for mars***, Springer; 1 edition, August 1, 2006.

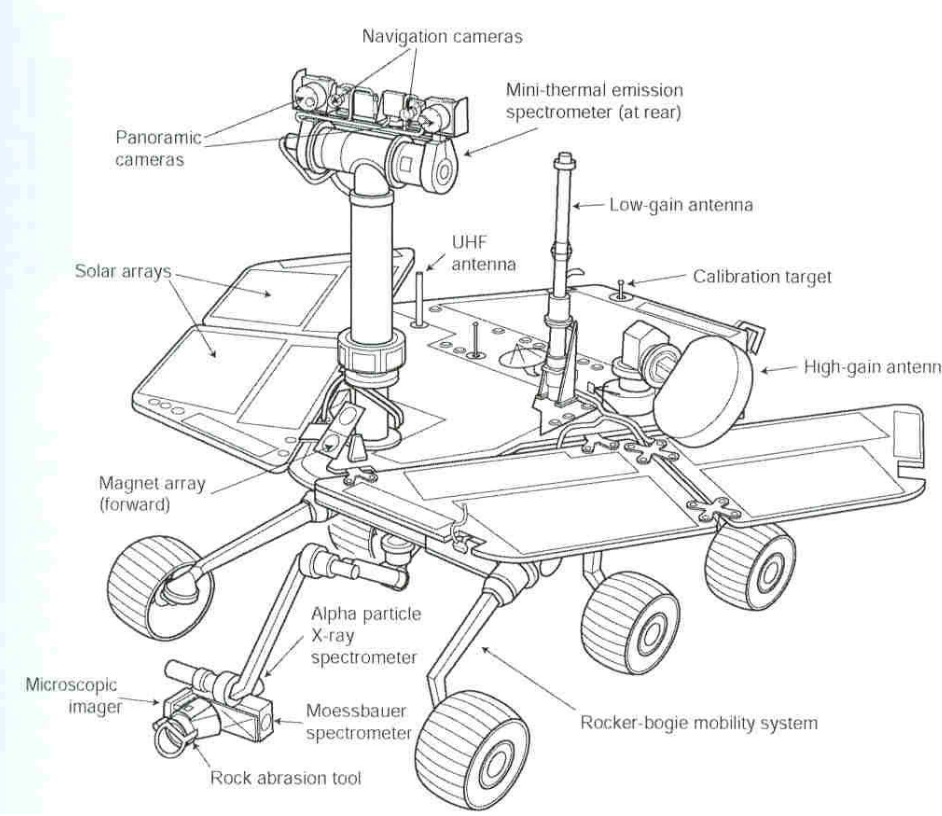
Mars Rovers

"Spirit" & "Opportunity"

AutoNav **PROBLEM before GLOBAL Planner uploaded in 2006**:

"When rover encounters a large hazard, …. hazard avoidance votes will not allow rover to drive through unsafe area, and waypoint votes will not allow enough deviation from straight-line path for rover to get around hazard. The rover becomes stuck…"

" A better waypoint vote metric is needed; something more accurate than Euclidean distance."



SOURCE: Carsen, A., Rankin, J., Fuguson, D., Stentz, A. (2007). **Global path planning on board the Mars Exploration Rovers**. In *Proceedings of the IEEE Aerospace Conference, 2007*. IEEE Press.

Image from: Young, A.H. ***Lunar and planetary rovers: the wheels of Apollo and the quest for mars***, Springer; 1 edition, August 1, 2006.

Mars Rovers

"Spirit" & "Opportunity"

Navigation

SOLUTION: Integration of **"Field D*" GLOBAL** Planner with existing AutoNav

Two main tasks:

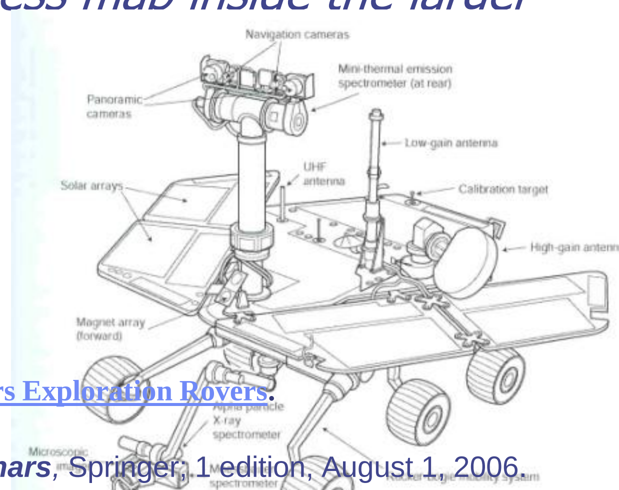
1) AutoNav provides terrain information to Field D*
2) Field D* provides steering recommendations to AutoNav

Field D* uses a grid "**Cost Map**" for a **world model**. Each cell has cost to traverse it

- Similar to AutoNav goodness map,
    - However goodness map is centered on rover and stores only local terrain info
- Field D* store a much larger map and is fixed to the environment

"Cells in goodness map can have "unknown" goodness. Field D cells must be assigned a cost. Initializing cells to low cost means rover will be more inclined to explore unseen regions. Initializing to a high cost means rover will prefer regions it has already seen; At each step, the position of the goodness map inside the larger cost map is determined."*

Also, GLOBAL maps can include terrain data from sources other than rovers (e.g., Earth observers)



VIDEO: http://mars.jpl.nasa.gov/msl/mission/technology/planetarymobility/

SOURCE: Carsen, A., Rankin, J., Fuguson, D., Stentz, A. (2007). Global path planning on board the Mars Exploration Rovers. In *Proceedings of the IEEE Aerospace Conference, 2007*. IEEE Press.

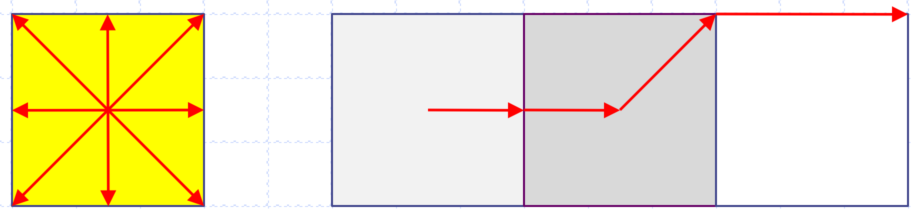
Image from: Young, A.H. ***Lunar and planetary rovers: the wheels of Apollo and the quest for mars***, Springer; 1 edition, August 1, 2006.

Mars Rovers

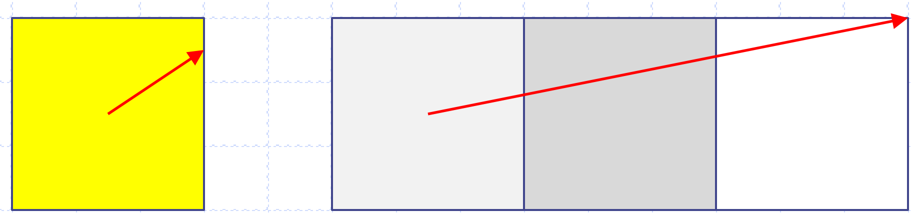
"Spirit" & "Opportunity"

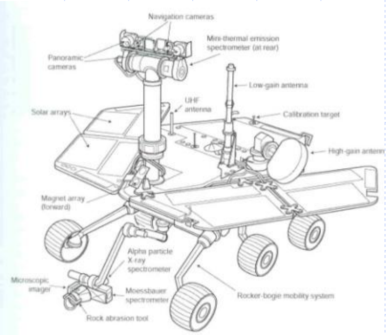
"Field D **GLOBAL** planner also uses interpolation to provide direct, low-cost paths through two-dimensional, grid-based representations of an environment."*

- Typical grid-based planners restrict paths to transitioning between adjacent grid cell centers or corners, resulting in unnecessary turning:



- The Field D* allows paths to transition through any point on any neighboring grid cell edge
  - Using linear interpolation to approximate the path cost to any point along a cell edge (i.e., cost of traversing box scaled to length of line through it)





SOURCE: Carsen, A., Rankin, J., Fuguson, D., Stentz, A. (2007). **Global path planning on board the Mars Exploration Rovers**. In *Proceedings of the IEEE Aerospace Conference, 2007*. IEEE Press.

Image from: Young, A.H. ***Lunar and planetary rovers: the wheels of Apollo and the quest for mars***, Springer; 1 edition, August 1, 2006.

Mars Rovers

"Spirit" & "Opportunity"

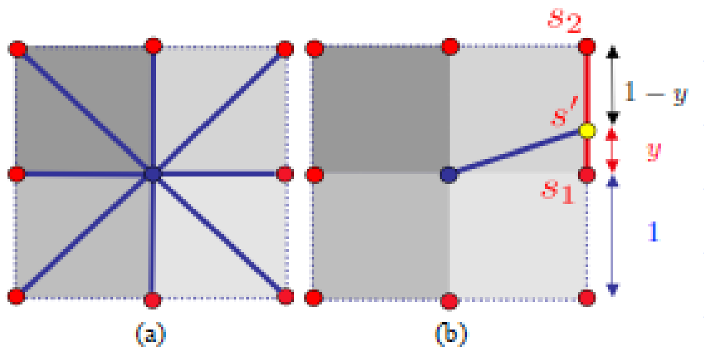


Figure 3. (a) The typical transitions (in blue) allowed from a node (shown at the center) in a uniform grid. Notice that only headings of 45 degree increments are available. (b) Using linear interpolation, the path cost of any point s' on an edge between two grid nodes s_1 and s_2 can be approximated. This can be used to plan paths through grids that are not restricted to just the 45 degree heading transitions.

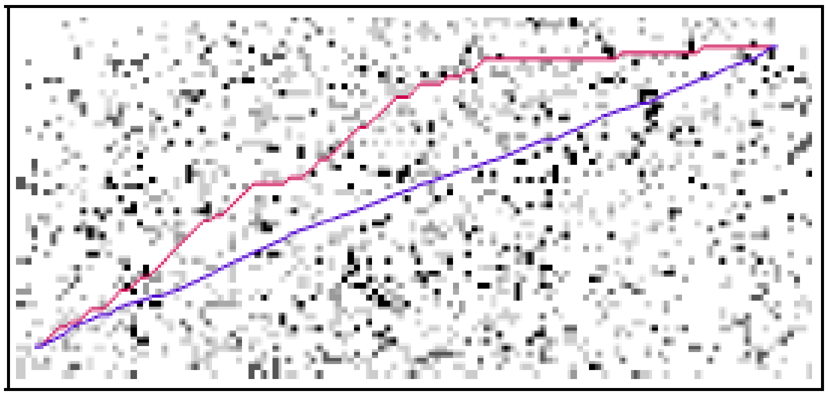
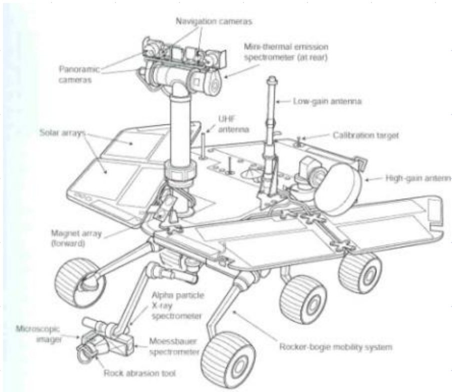


Figure 4. Paths produced by classic grid-based planners (red/top) and Field D* (blue/bottom) in a 150 × 60 uniform resolution grid. Darker cells represent higher-cost areas.



Images from: Carsen, A., Rankin, J., Fuguson, D., Stentz, A. (2007). [Global path planning on board the Mars Exploration Rovers](). In *Proceedings of the IEEE Aerospace Conference, 2007*. IEEE Press.

Image from: Young, A.H. ***Lunar and planetary rovers: the wheels of Apollo and the quest for mars***, Springer; 1 edition, August 1, 2006.

Mars Rovers

"Spirit" & "Opportunity"

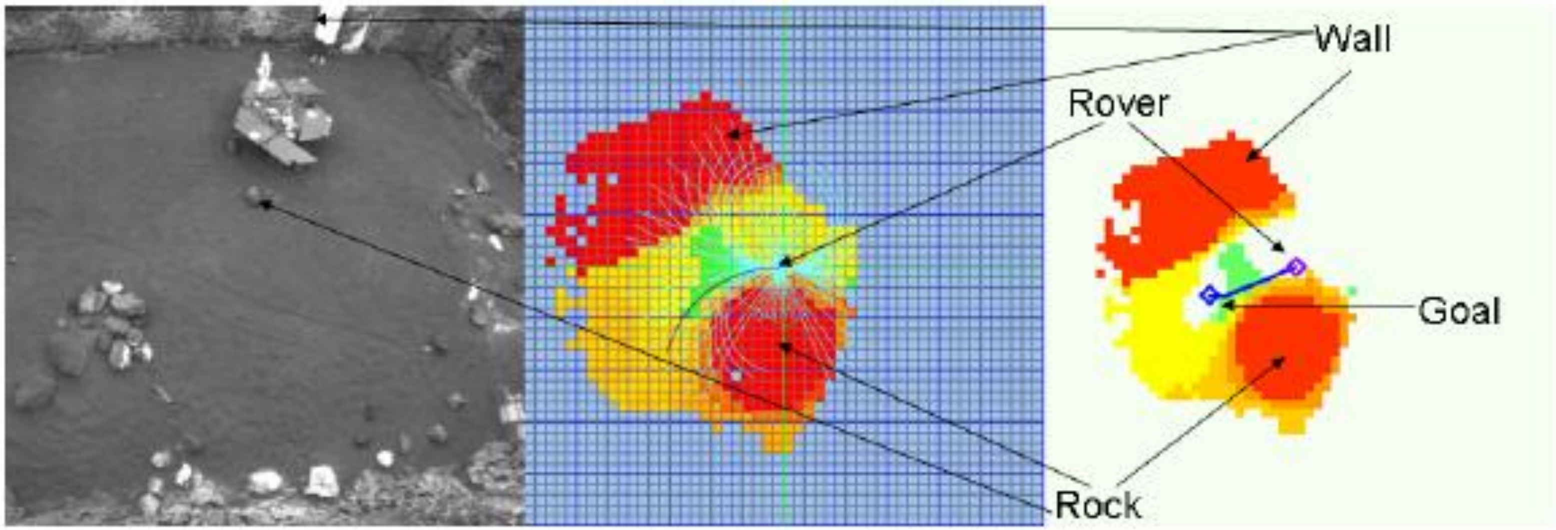


Figure 5. The left image is an overhead view of the rover. The middle image is the corresponding goodness map, and the Field D* cost map is shown in the right image. Blue cells have unknown traversability. All other cells are colored based on a gradient between green (high goodness/low cost) and red (low goodness/high cost). Note that the entire goodness map is presented, but only a small portion of the cost map is shown in here.

Image from: Carsen, A., Rankin, J., Fuguson, D., Stentz, A. (2007). **Global path planning on board the Mars Exploration Rovers**. In *Proceedings of the IEEE Aerospace Conference, 2007*. IEEE Press.

Image from: Young, A.H. ***Lunar and planetary rovers: the wheels of Apollo and the quest for mars***, Springer; 1 edition, August 1, 2006.

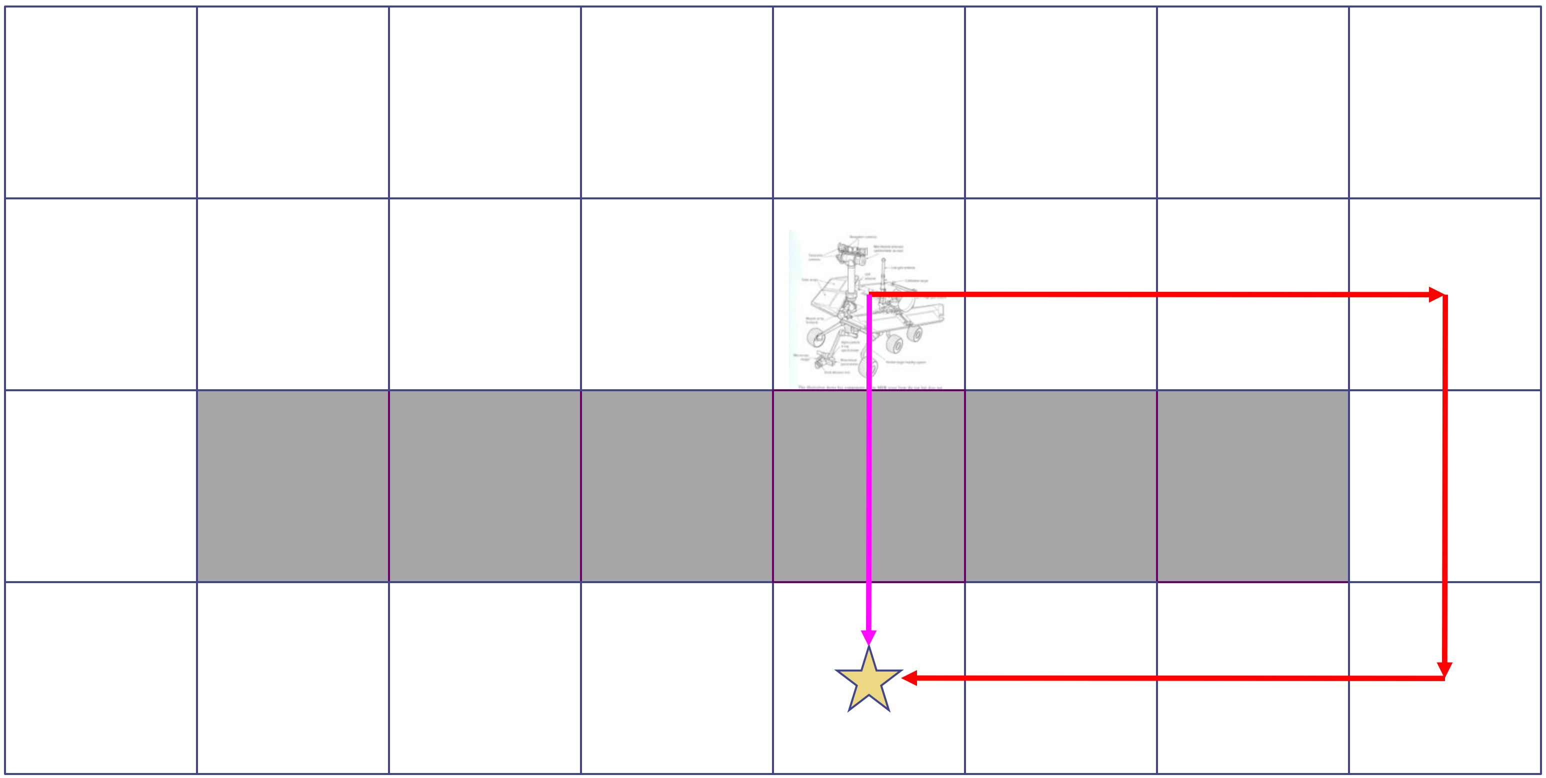
Mars Rovers

Navigation

“Spirit” & “Opportunity”

AutoNav **problem before GLOBAL Planner uploaded in 2006**:

*"When rover encounters a **large hazard**, …. hazard avoidance votes will not allow rover to drive through unsafe area, and waypoint votes will not allow enough deviation from straight-line path for rover to get around hazard. **The rover becomes stuck…"***



SOURCE: Carsen, A., Rankin, J., Fuguson, D., Stentz, A. (2007). **Global path planning on board the Mars Exploration Rovers**. In *Proceedings of the IEEE Aerospace Conference, 2007*. IEEE Press.

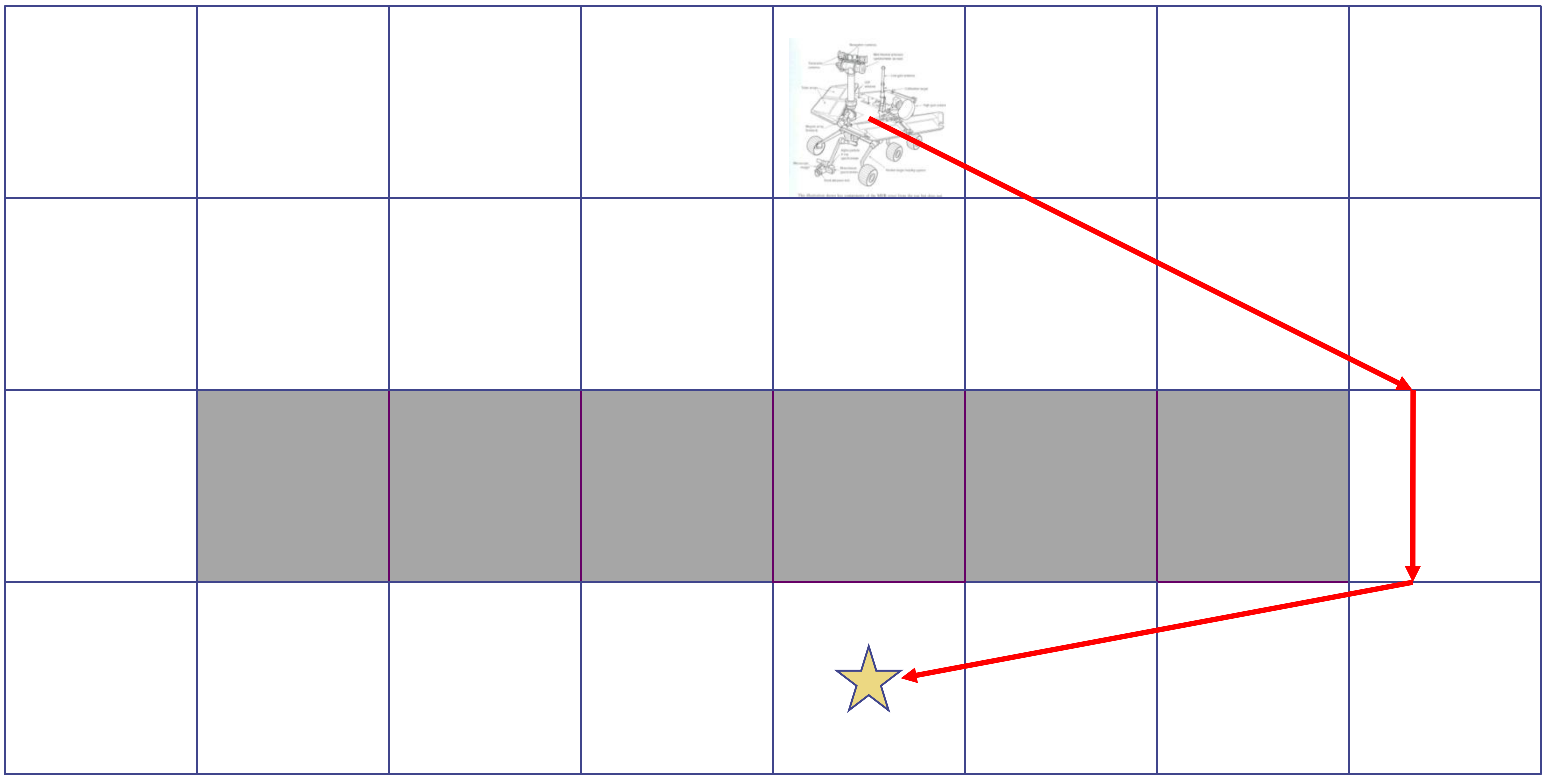
Image from: Young, A.H. ***Lunar and planetary rovers: the wheels of Apollo and the quest for mars***, Springer; 1 edition, August 1, 2006.

Mars Rovers

"Spirit" & "Opportunity"

Navigation

Likely **Field D* GLOBAL planner** SOLUTION (using forethought yielded by large cost map, plus *interpolative cost* to yield most direct low-cost path)



SOURCE: Carsen, A., Rankin, J., Fuguson, D., Stentz, A. (2007). **Global path planning on board the Mars Exploration Rovers**.
In *Proceedings of the IEEE Aerospace Conference, 2007*. IEEE Press.

Image from: Young, A.H. ***Lunar and planetary rovers: the wheels of Apollo and the quest for mars***, Springer; 1 edition, August 1, 2006.

Autonomous Navigation

- 2011: NASA ***Mars Science Lab Curiosity***
  Quickly navigate up to 5km from landing site, and find and sample scientific events including those requiring shallow subsurface exploration

AUTONOMY:
- **GLOBAL** path planner
- Terrain prediction (for slip compensation)
- "**AUTONOMOUS SCIENCE**" to predict & detect novel science events
  - Initially planned, but not implemented

SOURCE: Bajracharya, M., Maimone, M.W., and Helmick, D. (2008). **Autonomy for mars rovers: past, present, and future**. In *Computer*: December, 2008. (pp. 44-50). *IEEE Press. (available at http://marstech.jpl.nasa.gov/publications/z02_0102.pdf)*

Image from: http://www.extremetech.com/wp-content/uploads/2012/12/curiosity-self-portrait-mosaic-mt-sharp-640x353.jpg

See Mars Science Lab (Curiosity) **GLOBAL** path-planner:

http://mars.jpl.nasa.gov/msl/mission/technology/planetarymobility/

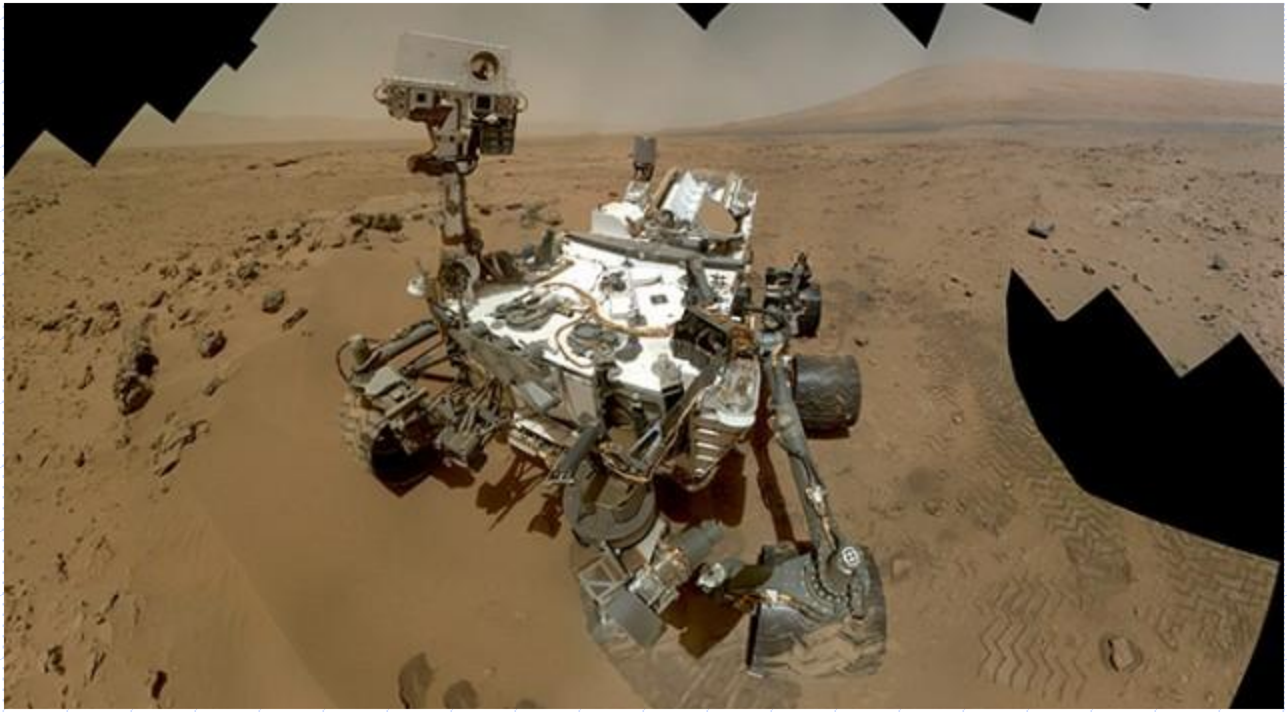


Image from: http://www.extremetech.com/wp-content/uploads/2012/12/curiosity-self-portrait-mosaic-mt-sharp-640x353.jpg

Mars Rovers

Navigation and Sensors

Mars Science Lab (Curiosity)

2011

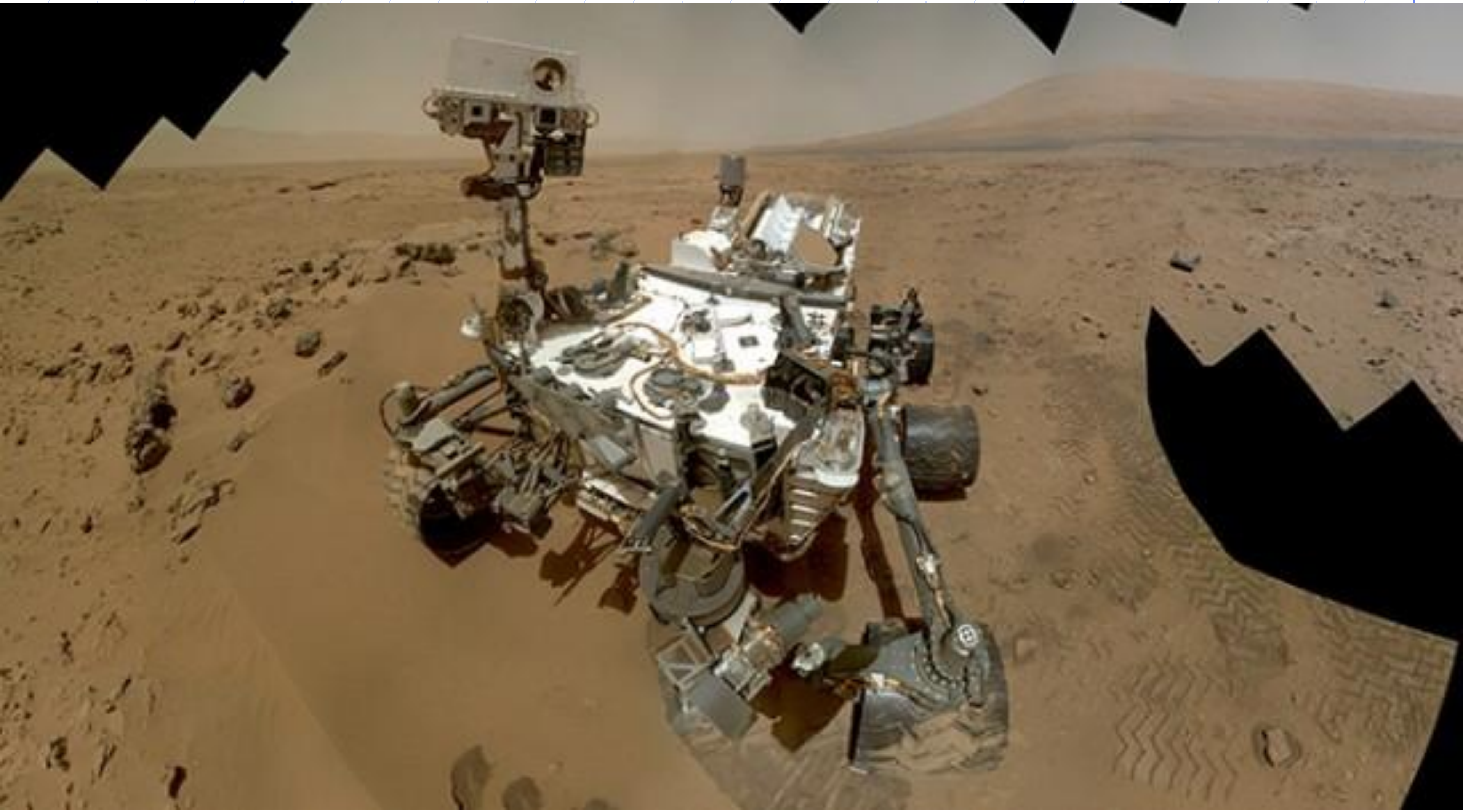


Image from: http://www.extremetech.com/wp-content/uploads/2012/12/curiosity-self-portrait-mosaic-mt-sharp-640x353.jpg

Autonomous Navigation

- 2016/2018: ESA ***Exomars***
- ***SEE more on Exomars:***
  - ***http://exploration.esa.int/mars/***
  - ***https://en.wikipedia.org/wiki/ExoMars***

AUTONOMY:
- **GLOBAL** path planner ?
- **AUTONOMOUS SCIENCE** ?

Image from: https://en.wikipedia.org/wiki/ExoMars

Some references on GLOBAL and Local path-planning:

Carsen, A., Rankin, J., Fuguson, D., Stentz, A. (2007). **Global path planning on board the Mars Exploration Rovers**. In *Proceedings of the IEEE Aerospace Conference, 2007*. IEEE Press.

Bajracharya, M., Maimone, M.W., and Helmick, D. (2008). **Autonomy for mars rovers: past, present, and future.** In *Computer*: December, 2008. (pp. 44-50). IEEE Press.

Coleman, D. and Wunderlich, J.T. (2008). **O^3: an optimal and opportunistic path planner (with obstacle avoidance) using voronoi polygons**. In *Proceedings of IEEE the 10th international Workshop on Advanced Motion Control*, Trento, Italy. vol. 1, (pp. 371-376). IEEE Press.

R. Siegwart and I. Nourbakhsh, ***Autonomous mobile robots***, Massachusetts Institute of Technology, 2004.

Wunderlich, J.T. (2004). **Simulating a robotic arm in a box: redundant kinematics, path planning, and rapid-prototyping for enclosed spaces**. In *Transactions of the Society for Modeling and Simulation International*: Vol. 80. (pp. 301-316). San Diego, CA: Sage Publications. *(NOTE: Although this paper is about robotic arms, not rovers, the path planning of the arm trajectories, especially the end-effector, is similar to rover navigation)*

Wunderlich, J.T. (2001). Simulation vs. real-time control; with applications to robotics and neural networks. In *Proceedings of 2001 ASEE Annual Conference & Exposition, Albuquerque, NM*: (session 2793), [CD-ROM]. ASEE Publications.

Some rovers designed for two specific events on earth at the [IGVC (Intelligent Ground Vehicle Competition)]

1) Visit 10 GPS way-points as quickly as possible while avoiding large traffic barrels, fencing, and out-of-bound white lines painted on grass

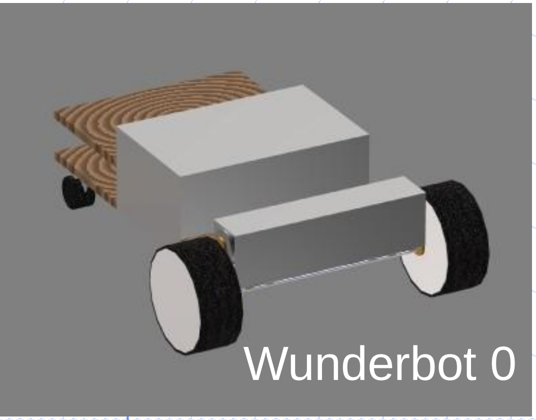
2) Navigate a course defined by a pair of white lines painted on grass while avoiding large traffic barrels, fencing, and blockades. Also be able to go up and down a ramp

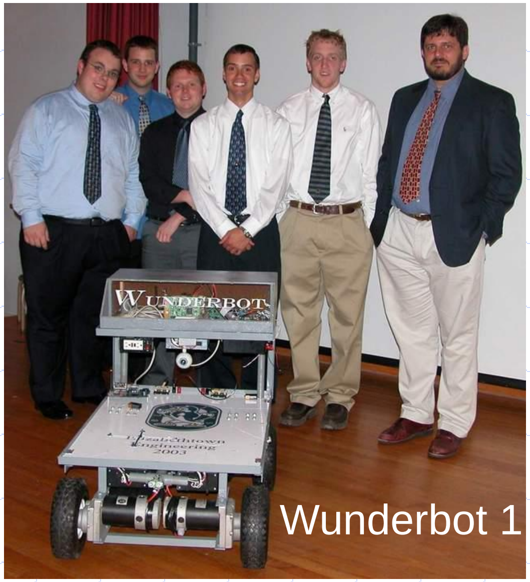
NEED AUTONOMY

- No tele-operation allowed; except for maneuvering between events

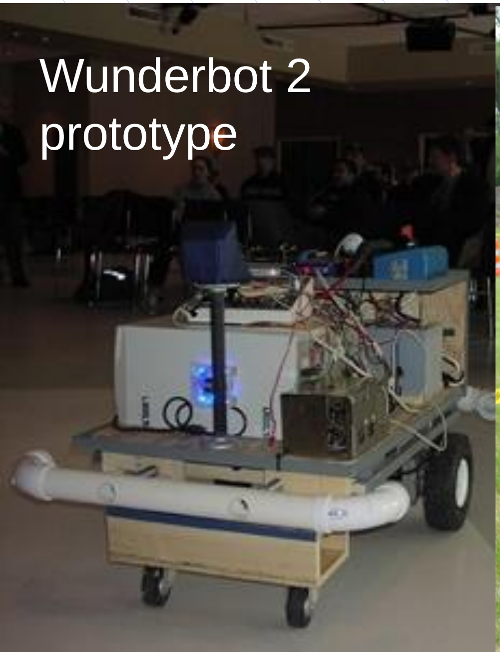
See evolution of navigation and sensors since 2000 here:
http://users.etown.edu/w/wunderjt/Weblab_archive.htm

All recent Wunderbots share website:
http://www2.etown.edu/wunderbot/


Wunderbot 0



Wunderbot 1


Wunderbot 2 prototype

Wunderbot 3

Wunderbot 4

Implementation and integration of the most recent Wunderbot systems:

- Wunderbot - Main VI Labview Tutorial
- Wunderbot - GPS Subsystem Labview Tutorial
- Wunderbot - LADAR Subsystem Labview Tutorial
- Wunderbot - JAUS Subsystem Labview Tutorial
- Wunderbot - Vision Subsystem Labview Tutorial
- Wunderbot - Motor Control Subsystem Labview Tutorial
- Wunderbot - Digital Compass Subsystem Labview Tutorial
- Wunderbot - MCglobal08 Subsystem Labview Tutorial
- nanoLC Robot Simulation


Wunderbot 4

And theory and design decisions here:

[1] Painter, J. and Wunderlich, J.T. (2008). **Wunderbot IV: autonomous robot for international competition**. In *Proceedings of the 12th World Multi-Conference on Systemics, Cybernetics and Informatics: WMSCI 2008, Orlando, FL*: (pp. 62-67). And HERE

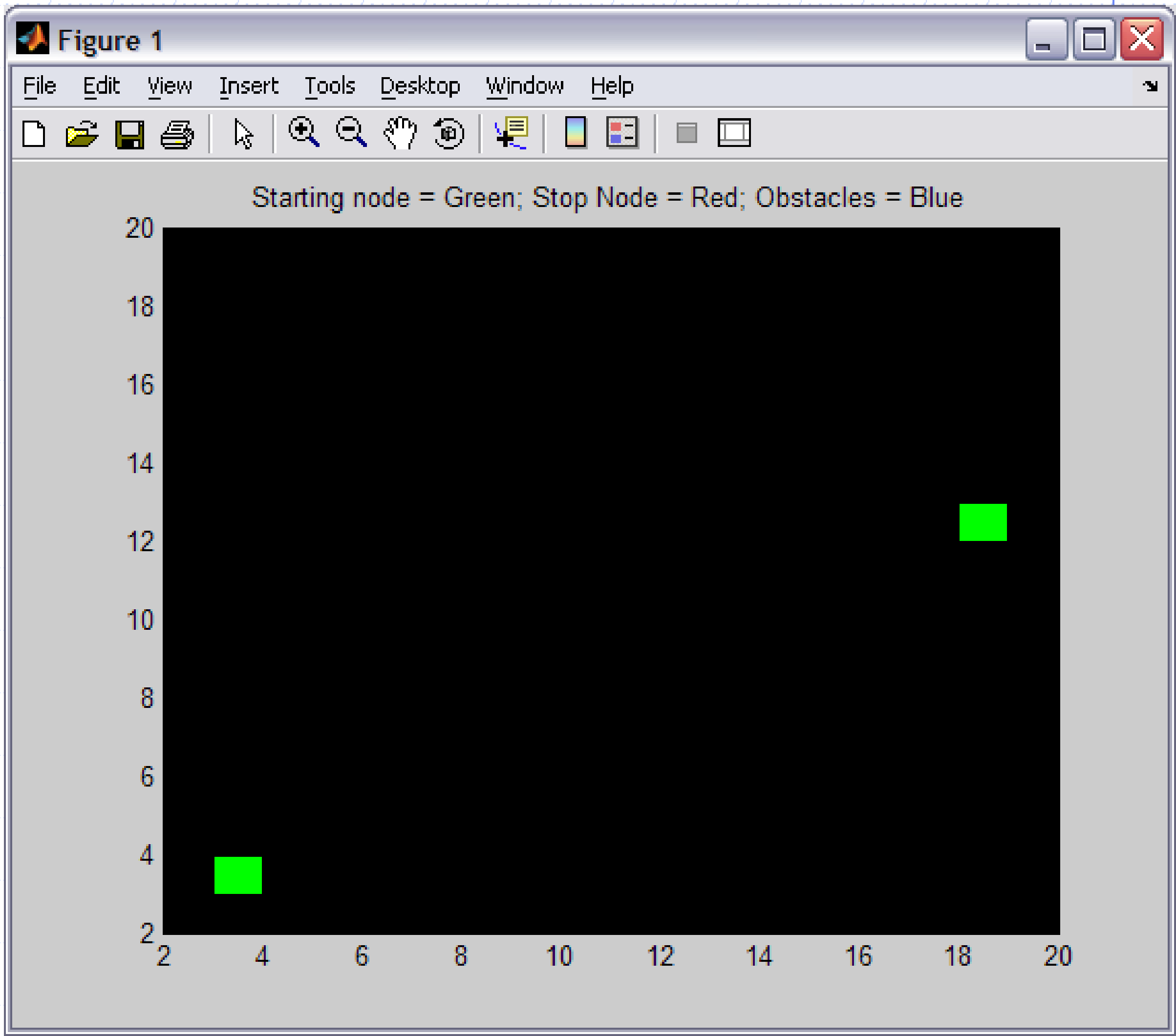
[2] Coleman, D. and Wunderlich, J.T. (2008). **O^3: an optimal and opportunistic path planner (with obstacle avoidance) using voronoi polygons**. In *Proceedings of IEEE the 10th international Workshop on Advanced Motion Control, Trento, Italy.* vol. 1, (pp. 371-376). IEEE Press.

[3] JAUS wireless packetized communication by Jeremy Crouse

Wunderbot 4 LOCAL Path-Planner

by David Colman (advisor: J. Wunderlich)

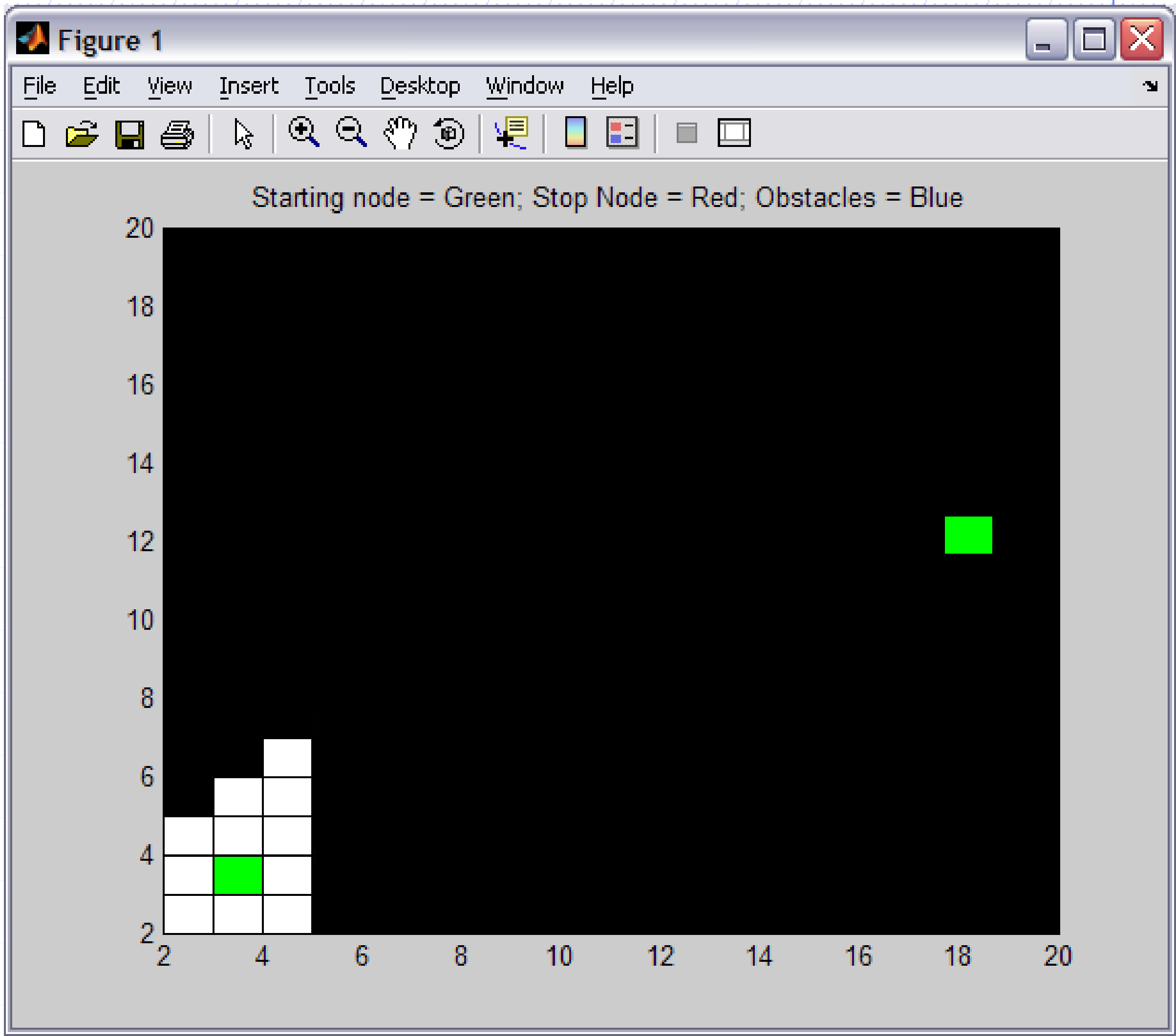
PRELIMINARY RESEARCH



Wunderbot 4 LOCAL Path-Planner

by David Colman (advisor: J. Wunderlich)

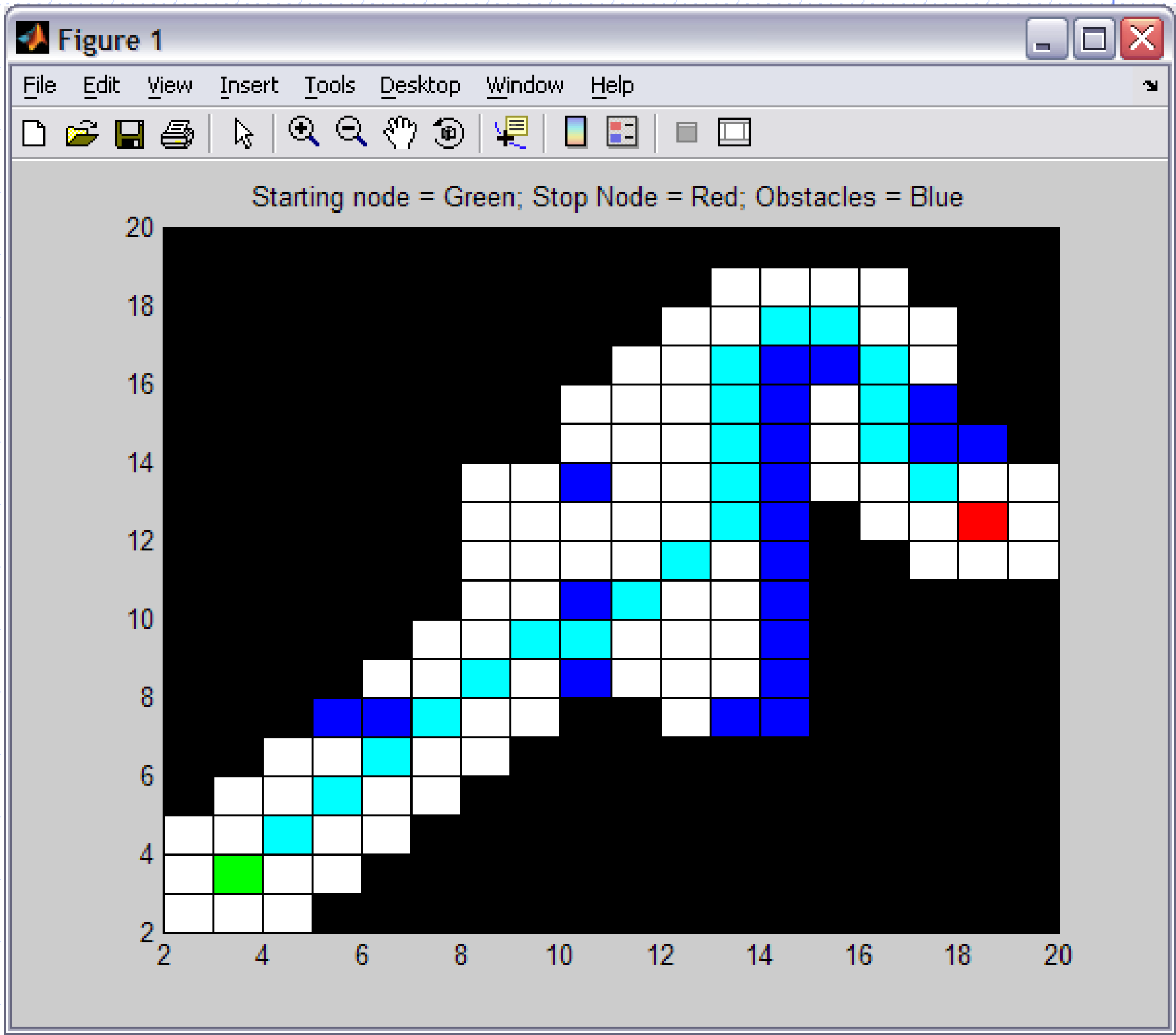
PRELIMINARY RESEARCH



Wunderbot 4 LOCAL Path-Planner

by David Colman (advisor: J. Wunderlich)

PRELIMINARY RESEARCH



Wunderbot 4 combined GLOBAL/LOCAL Path-Planner by David Colman (advisor: J. Wunderlich)

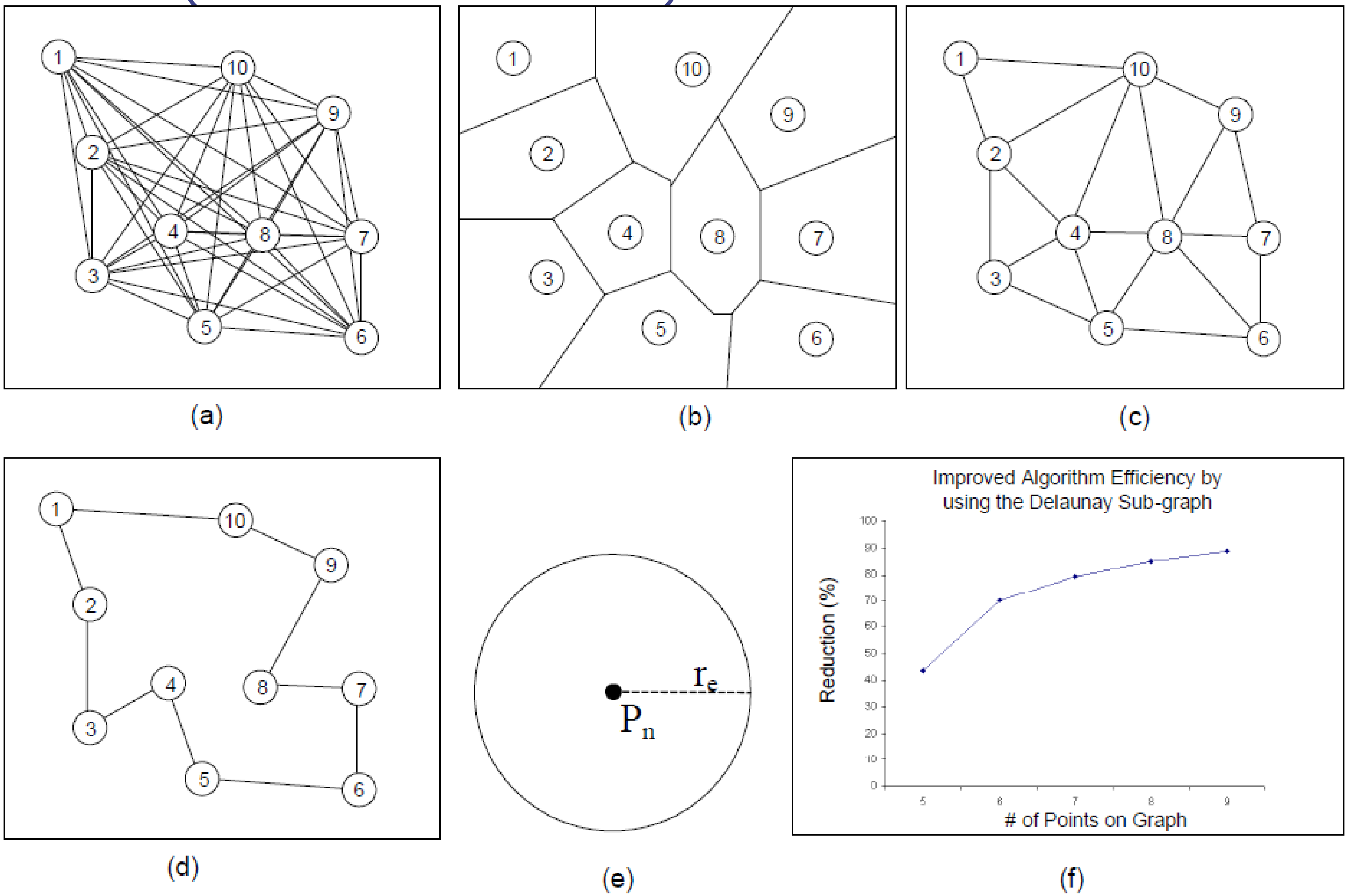


Fig. 1. (a) Environment of 10 goal nodes; (b) Voronoi Diagram of environment; (c) Delaunay Triangulation of environment; (d) Hamiltonian circuit derived by (c); (e) Expanded node showing r_e (f) Reduction in processing time using (c) instead of (a).

Coleman, D. and Wunderlich, J.T. (2008). **O³: an optimal and opportunistic path planner (with obstacle avoidance) using voronoi polygons**. In *Proceedings of IEEE the 10th international Workshop on Advanced Motion Control, Trento, Italy.* vol. 1, (pp. 371-376). IEEE Press.

Wunderbot 4 combined GLOBAL/LOCAL Path-Planner

by David Colman (advisor: J. Wunderlich)

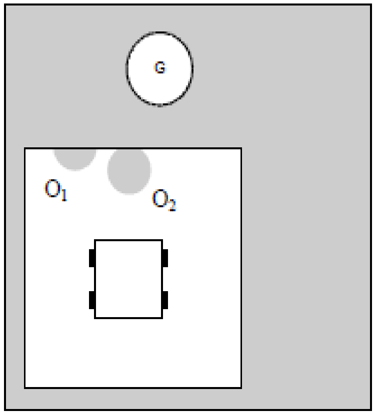


Fig. 3. Dynamic window approach. Obstacles are seen at O_1 and O_2 and the goal node is labeled G.

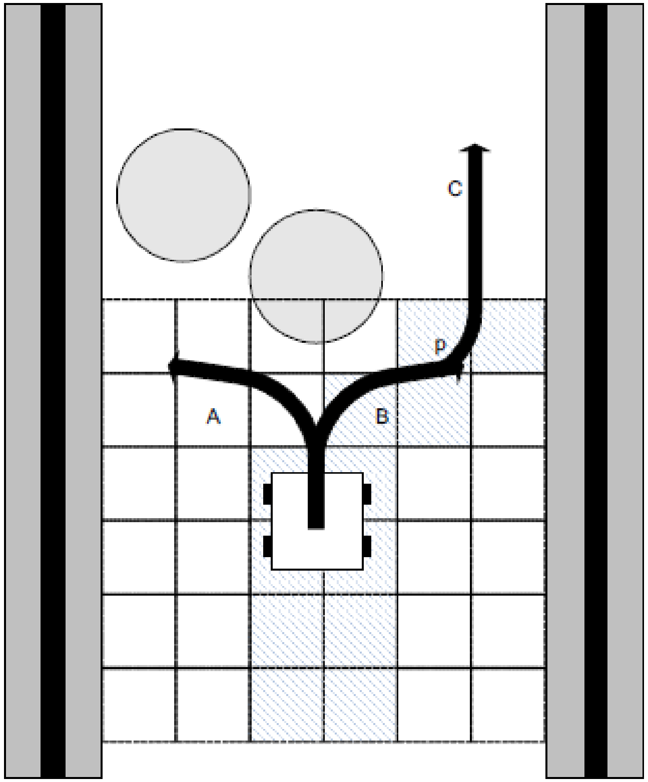


Fig. 4. Cell decomposition of region where one obstacle is in the middle of the robot's vision. A decision needs to be made to take path A (left curve) or path B (right curve). Using the heuristics invoked in A* path B is chosen and the best-fit curve (path C) is implemented at point P. The curvature at point P is equal to r_1. The grid surrounding the robot represents the environmental map being developed with A*. Its size is equal to the dynamic window shown in Fig. 3 and is govern by available sensors.

Coleman, D. and Wunderlich, J.T. (2008). **O[3]: an optimal and opportunistic path planner (with obstacle avoidance) using voronoi polygons**. In *Proceedings of IEEE the 10th international Workshop on Advanced Motion Control, Trento, Italy.* vol. 1, (pp. 371-376). IEEE Press.

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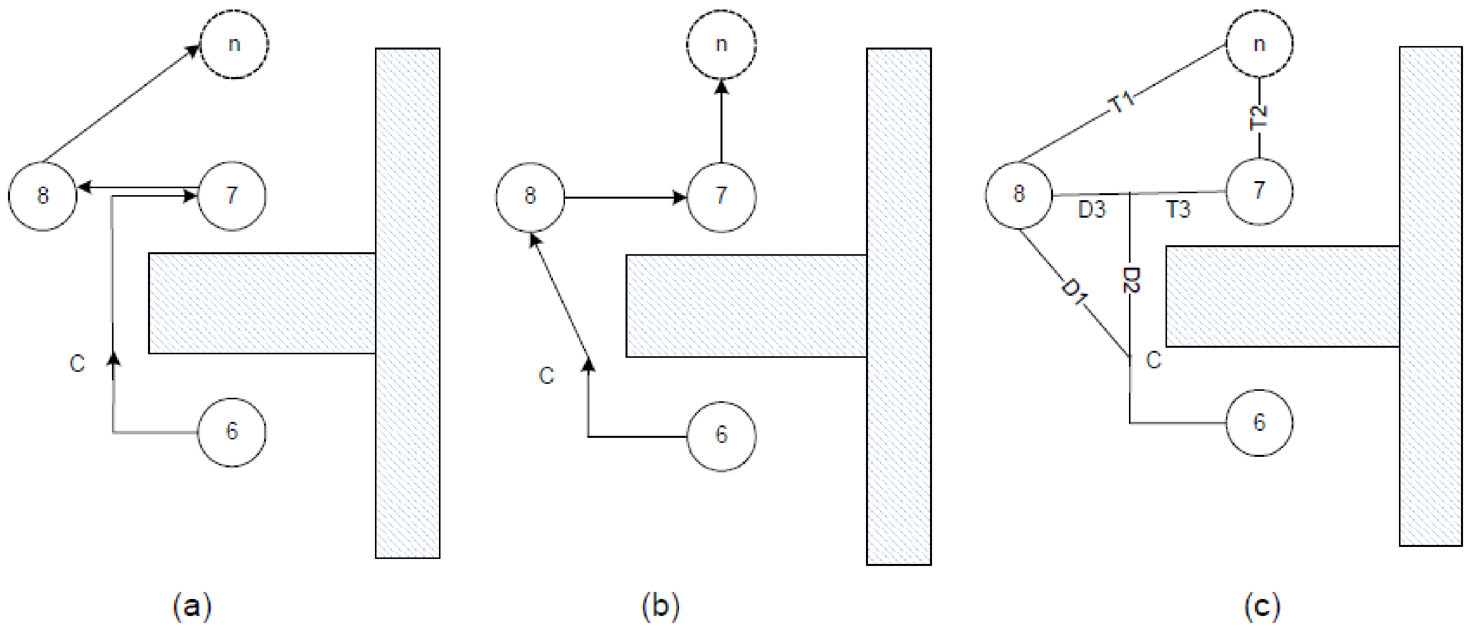

Fig. 5. Following the path prescribed in Figure 1(d) the robot should traverse the points as shown in (a). With the discovery of the obstacle it changes points to traverse the path shown in (b). (c) The combination of (a) and (b) for γ analysis.

Coleman, D. and Wunderlich, J.T. (2008). **O³: an optimal and opportunistic path planner (with obstacle avoidance) using voronoi polygons**. In *Proceedings of IEEE the 10th international Workshop on Advanced Motion Control, Trento, Italy.* vol. 1, (pp. 371-376). IEEE Press.

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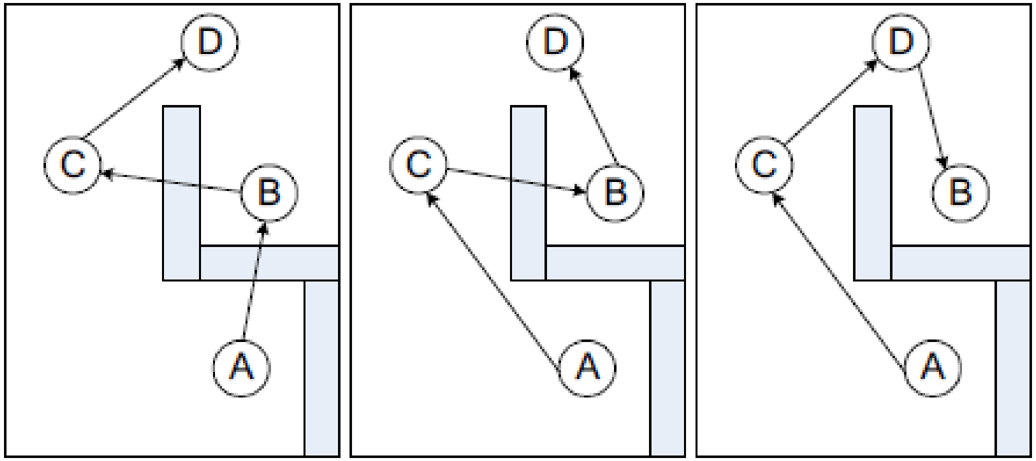

Fig. 6. Map with more than one point of opportunity. The original TSP dictates an A-B-C-D path. After the γ analysis, A-C-D-B is locally opportunistic and globally optimal.

See more at:

Coleman, D. and Wunderlich, J.T. (2008). **O[3]: an optimal and opportunistic path planner (with obstacle avoidance) using voronoi polygons**. In *Proceedings of IEEE the 10th international Workshop on Advanced Motion Control, Trento, Italy.* vol. 1, (pp. 371-376). IEEE Press.

Wunderbot 4 combined GLOBAL/LOCAL Path-Planner

Navigation Sensors

(a) (b)

Fig. 7. (a) Phoenix Contact SFN 5TX five-port switch, to which is connected, from left to right: camera, PC, wireless access point. (b) Trimble AgGPS 114.

SOURCE: Painter, J. and Wunderlich, J.T. (2008). **Wunderbot IV: autonomous robot for international competition.** In *Proceedings of the 12th World Multi-Conference on Systemics, Cybernetics and Informatics: WMSCI 2008, Orlando, FL*: (pp. 62-67). And HERE

Wunderbot 4 combined GLOBAL/LOCAL Path-Planner

Navigation Sensors

(a) (b)

Fig. 5. (a) One of two SICK LMS 200 laser range-finders. (b) Cognex DVT Legend 554C XE camera.

Obstacle Avoidance

SOURCE: Painter, J. and Wunderlich, J.T. (2008). **Wunderbot IV: autonomous robot for international competition**. In *Proceedings of the 12th World Multi-Conference on Systemics, Cybernetics and Informatics: WMSCI 2008, Orlando, FL*: (pp. 62-67). And HERE

Wunderbot 4 combined GLOBAL/LOCAL Path-Planner VISION
by James Painter (advisor: J. Wunderlich)

Navigation Sensors

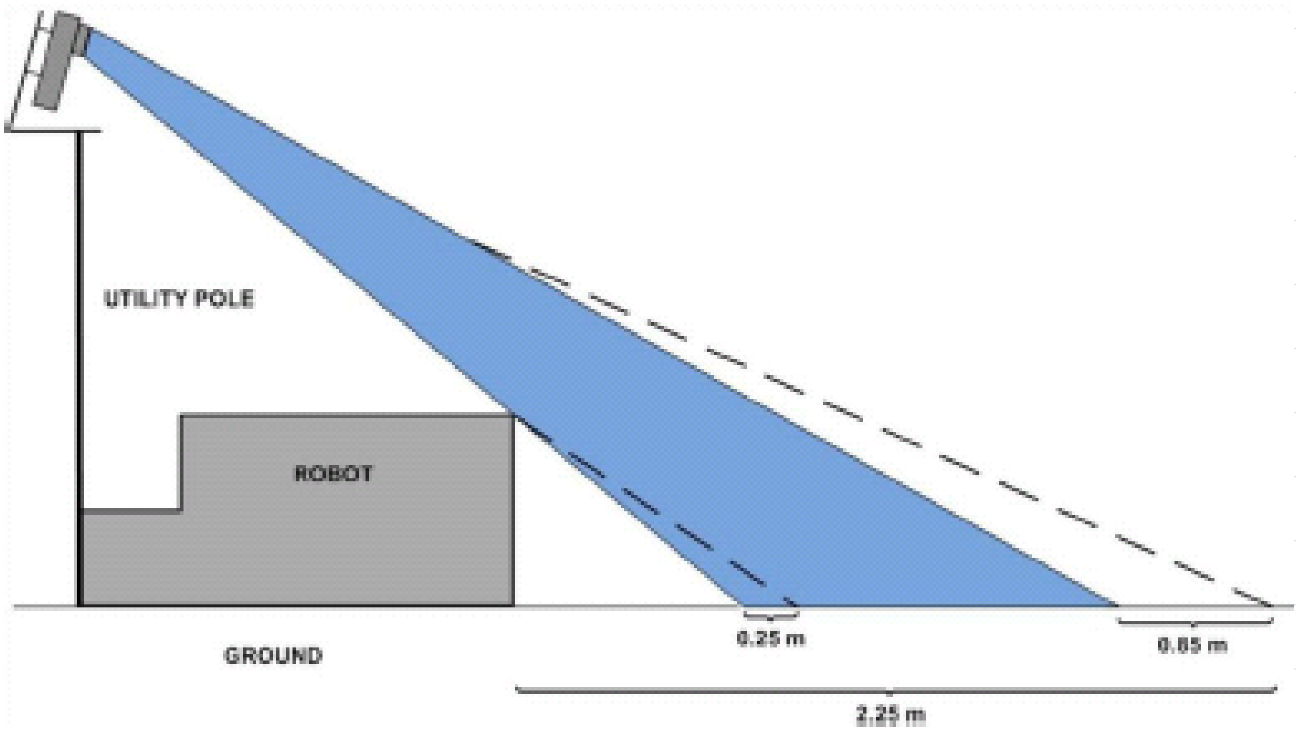

Fig. 2. Camera viewable region, with camera mounted directly above rear bumper (blue fill) and with camera shifted back 40.5cm from rear bumper (dashed lines).

Obstacle Avoidance

SOURCE: Painter, J. G. (2008). **Vision system for Wunderbot IV autonomous robot**. *Elizabethtown College research report.*

Wunderbot 4 combined GLOBAL/LOCAL Path-Planner VISION
by James Painter (advisor: J. Wunderlich)

Navigation Sensors

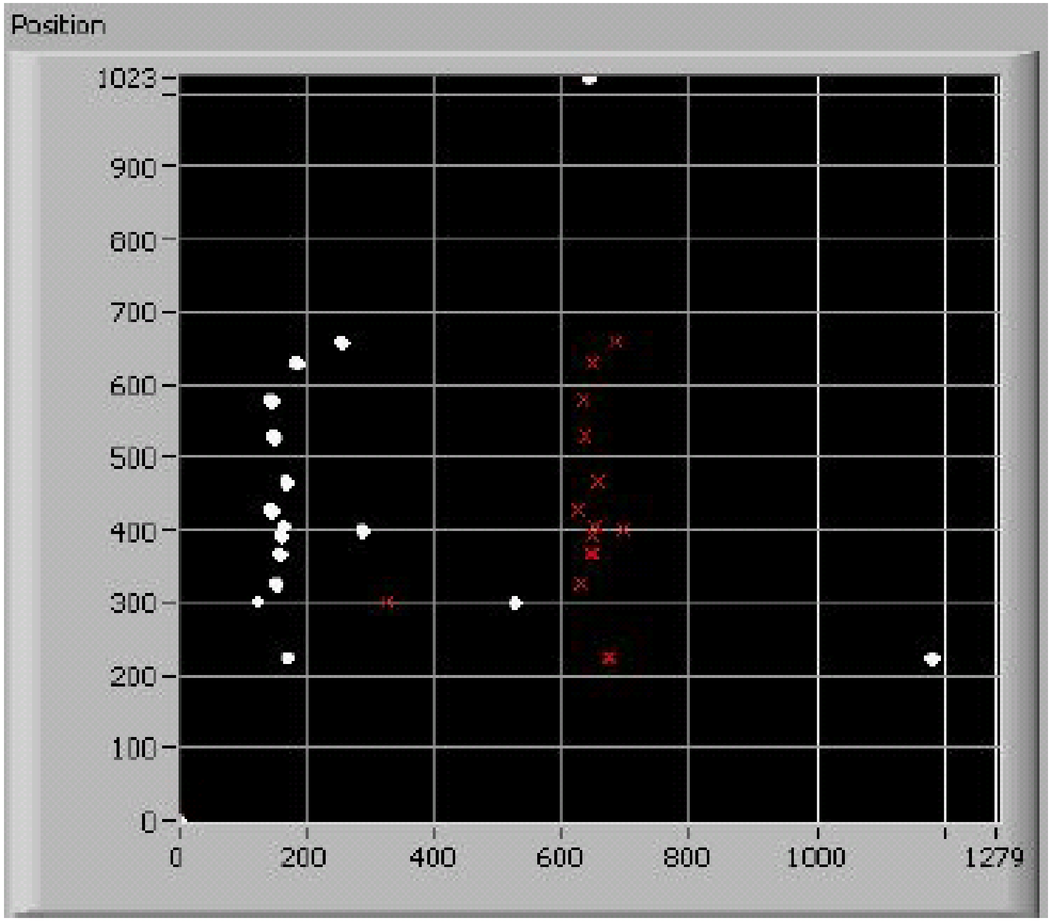

Fig. 4. (a) Detected white lines and calculated target points, both plotted on local map using pixel scale.

Obstacle Avoidance

SOURCE: : Painter, J. G. (2008). **Vision system for Wunderbot IV autonomous robot**. *Elizabethtown College research report.*

Wunderbot 4 combined GLOBAL/LOCAL Path-Planner VISION
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Navigation Sensors

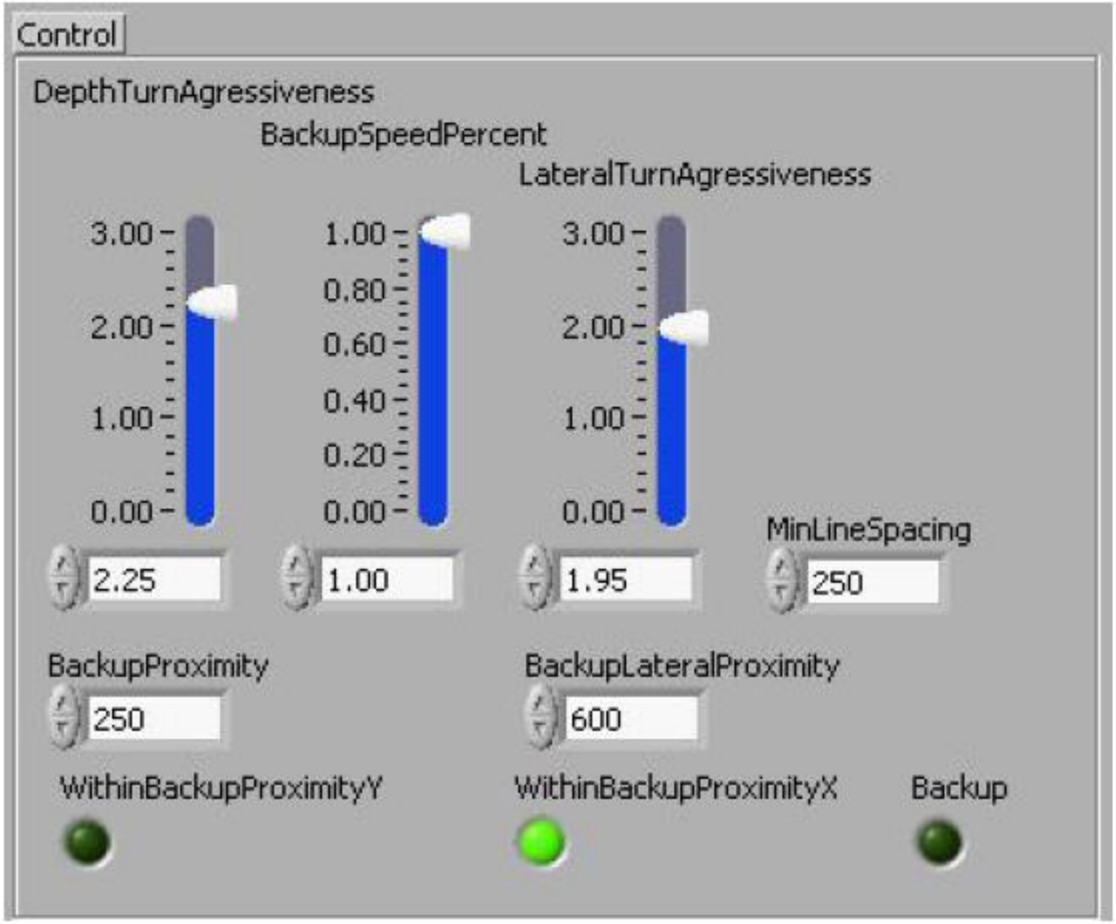


Fig. 4. (b) LabVIEW control panel with adjustments for vehicle movement.

Obstacle Avoidance

SOURCE: : Painter, J. G. (2008). **Vision system for Wunderbot IV autonomous robot**. *Elizabethtown College research report.*

Navigation

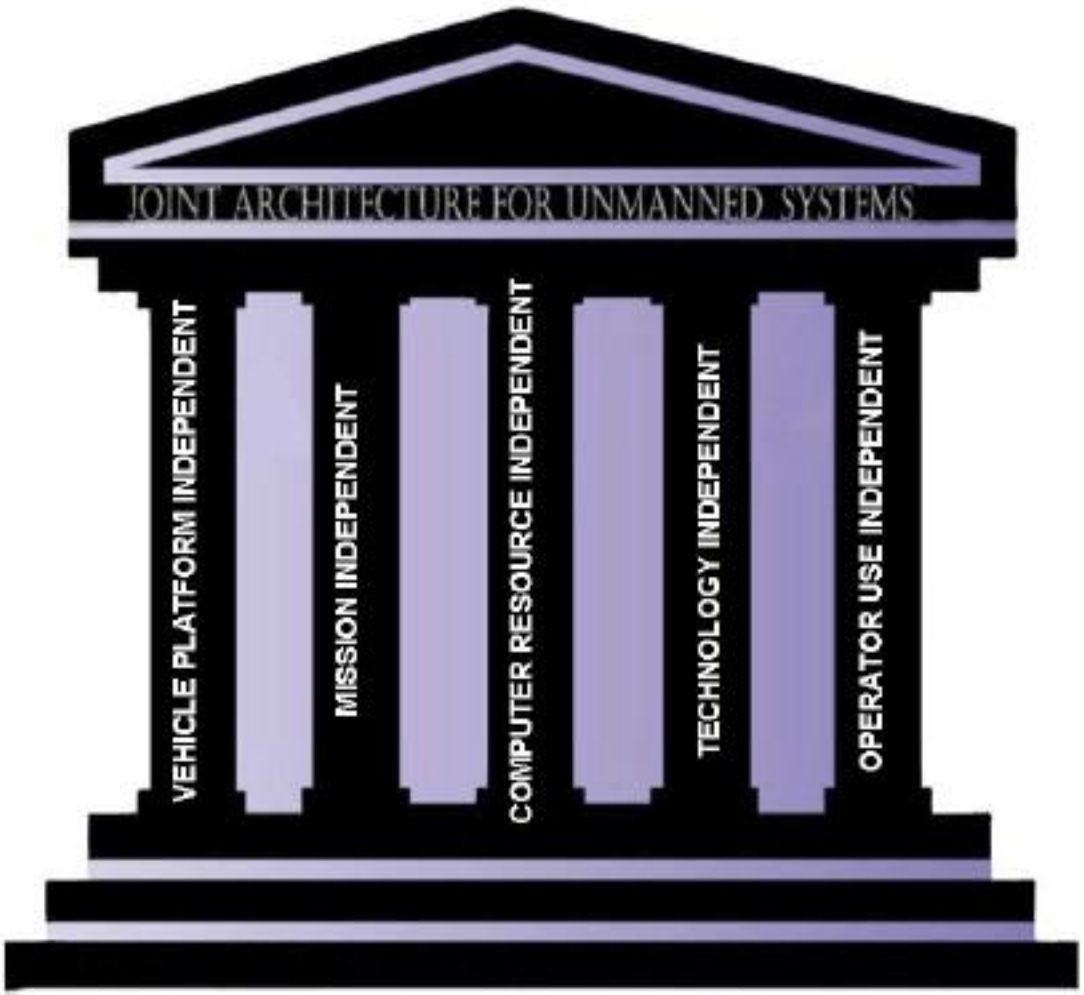


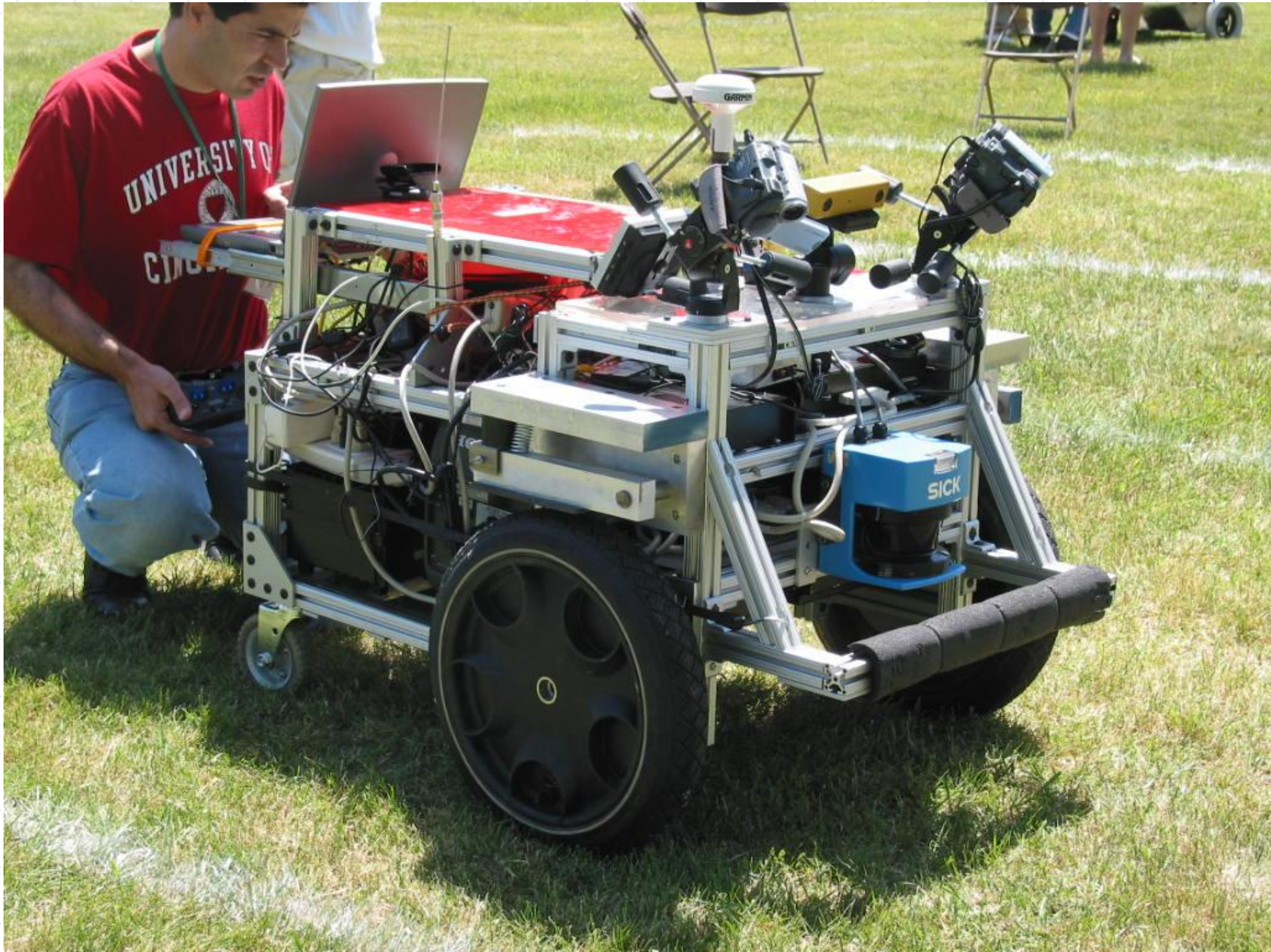
Figure 1: JAUS Independence requirements [3]

Although Wunderbots are fully autonomous, the IGVC awards those who can respond to "JAUS"

SOURCE: : Crouse, J. (2008). **The joint architecture for unmanned systems: a subsystem of the wunderbot 4**. *Elizabethtown College research report.*


IGVC
IGVC

IGVC Competitors:
Separate camera to see each parallel white line painted on grass



IGVC Competitors:

Camera mounted high to take in a wide image of surrounding environment

IGVC Competitors:
Two GPS units for fault tolerance and precise positioning

IGVC Competitors:
Tall thin body allows easy navigation in and out (and through) tight spaces

IGVC Competitors:

"Articulated body" (like an ant) allows easy navigation in and out (and through) tight spaces

Europa Rover

Optional course project Concept Paper

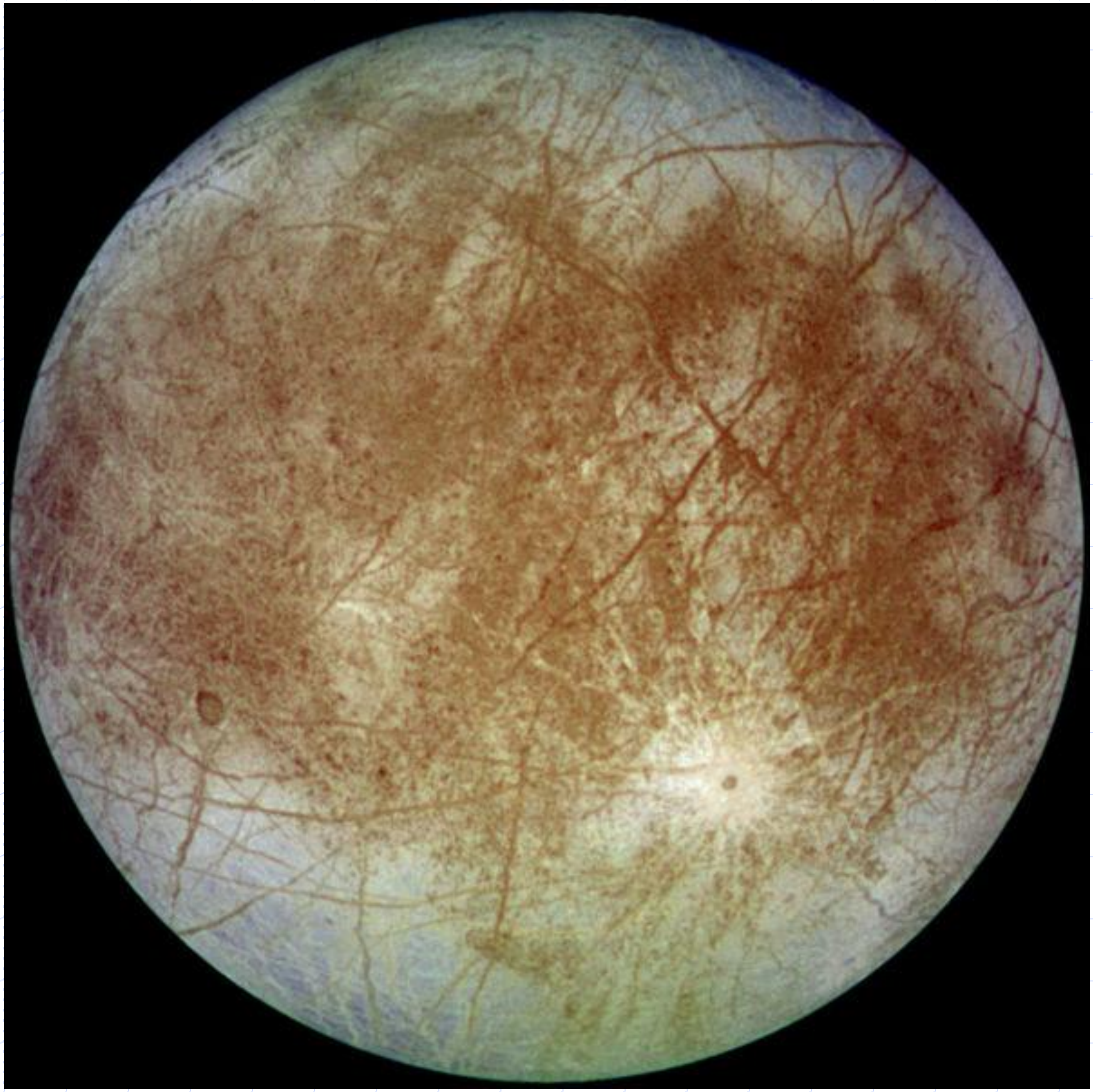


Image from: http://photojournal.jpl.nasa.gov/catalog/PIA00502

Europa
is also much
further from
Earth than Mars

And therefore
more
AUTONOMOUS
navigation
needed

Europa Rover Navigation

Possible course project

Maneuver on flat icy surface, then drill through 200 meters of ice

When water reached, either:
(1) Act as UUV, or
(2) Deploy a swarm of 100 10cm long UUV's

Communicate with UUV's if option (2) chosen

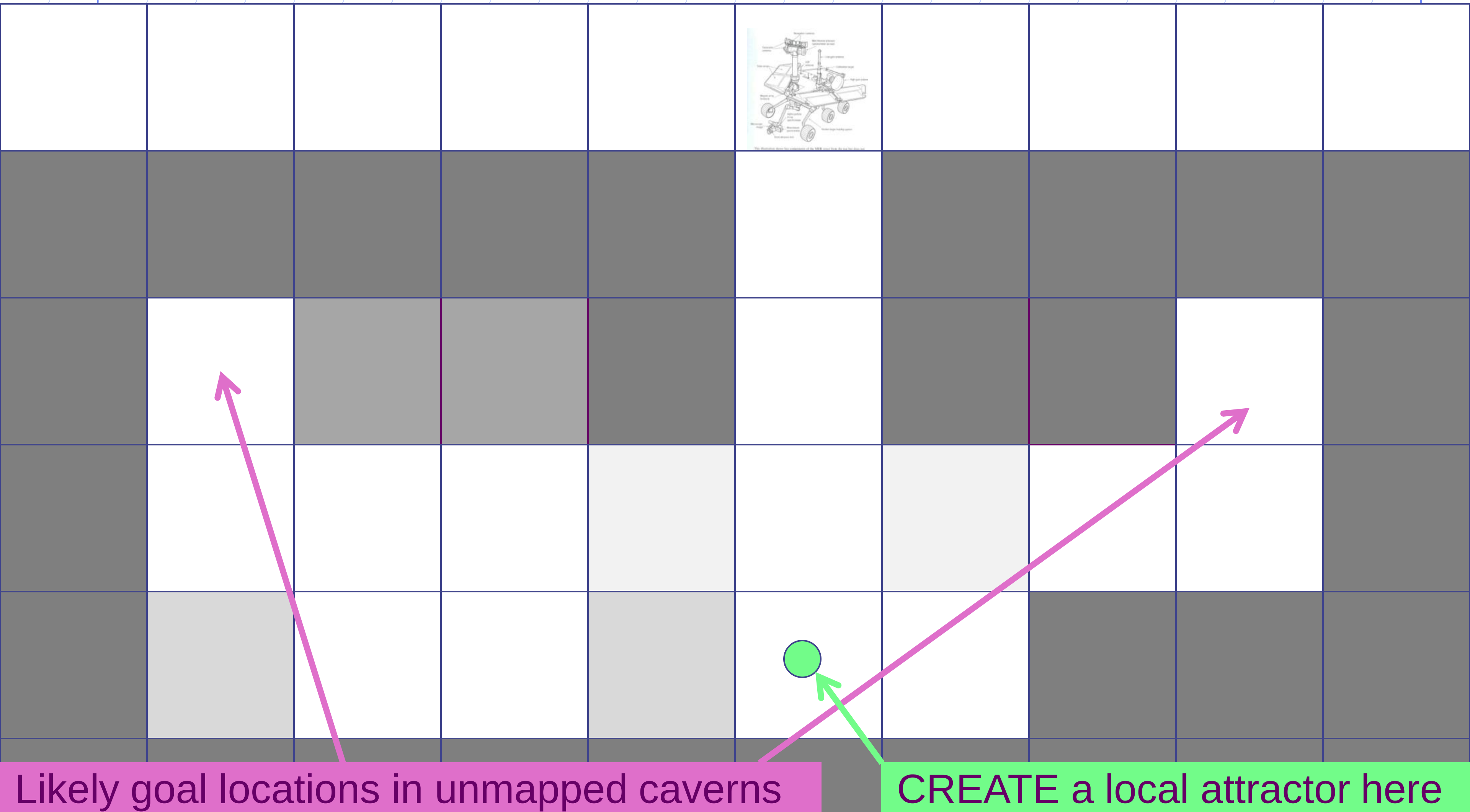
Communicate with base station that is also communicating with several orbiters and earth. The base station is also running a **concurrent simulation** to the rover's **LOCAL** real-time code and will be building a **GLOBAL environmental map** of the region of Europa being explored. This information should also be communicated back to the rover, -- and then to UUV's if option (2) is chosen.

http://www.mapaplanet.org/explorer/help/data_set.html

ADVICE

Unknown goal location(s) in a cluttered **UNMAPPED** environment

CONSIDER CREATING **LOCAL ATTRACTOR(S)** by using Heuristics

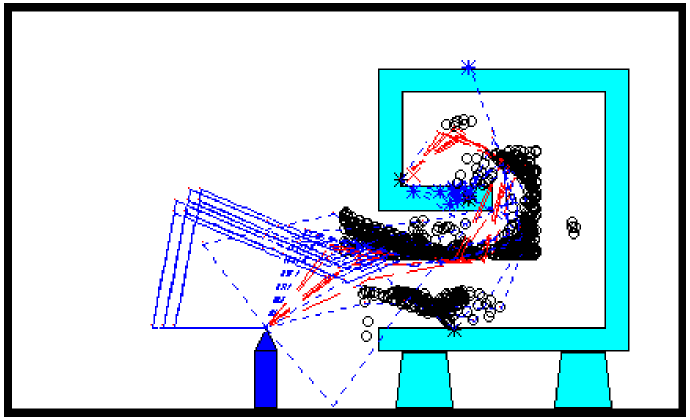


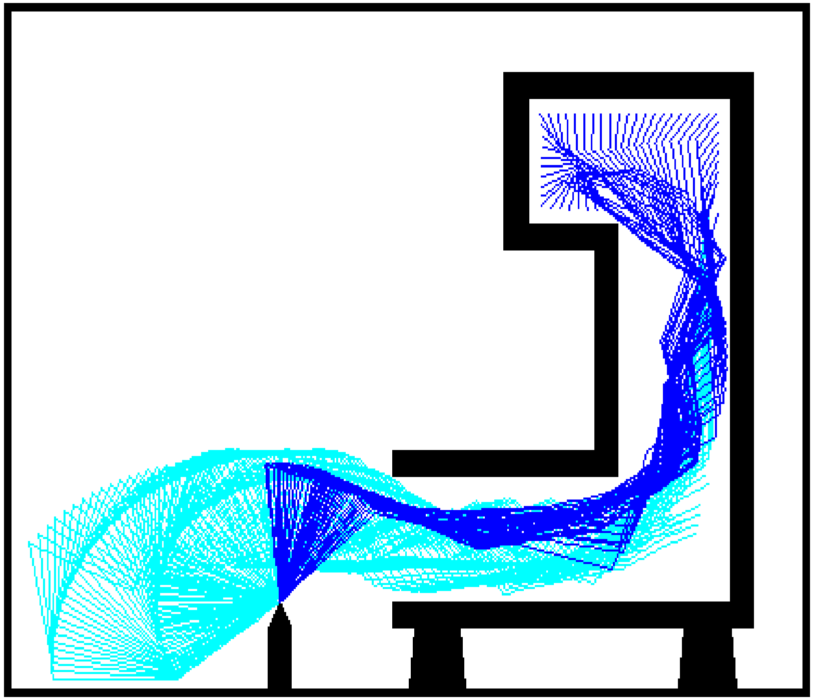
ADVICE

Navigation

For more on **LOCAL ATTRACTORS**, see:

Wunderlich, J.T. (2004). Simulating a robotic arm in a box: redundant kinematics, path planning, and rapid-prototyping for enclosed spaces. In *Transactions of the Society for Modeling and Simulation International*: Vol. 80. (pp. 301-316). San Diego, CA: Sage Publications.

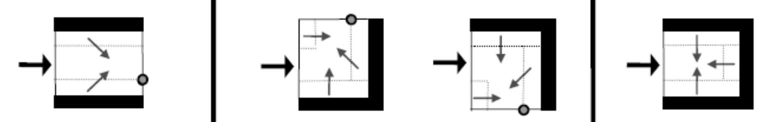




ADVICE

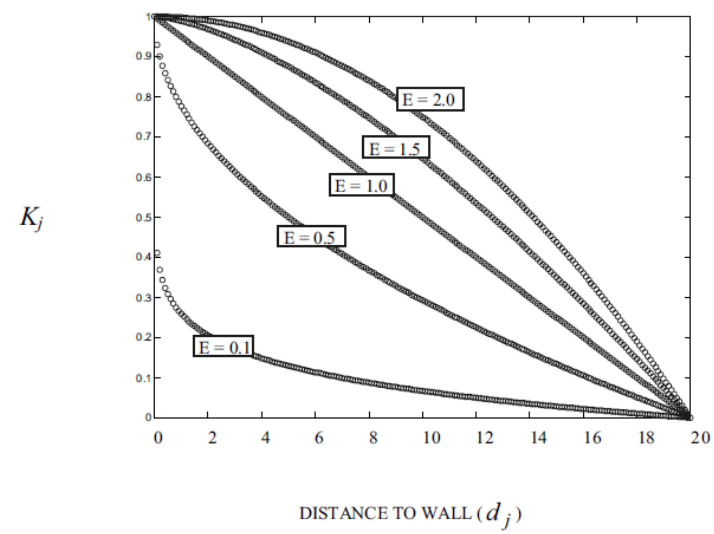
For more on **LOCAL ATTRACTORS**, and use of "**POTENTIAL FIELDS**" for obstacle avoidance, see:

Wunderlich, J.T. (2004). Simulating a robotic arm in a box: redundant kinematics, path planning, and rapid-prototyping for enclosed spaces. In *Transactions of the Society for Modeling and Simulation International*: Vol. 80. (pp. 301-316). San Diego, CA: Sage Publications.

	TUNNEL	LEFT ELBOW / RIGHT ELBOW	TERMINATOR
ATTRACTIVE POLE (●) REPELLING ANGLES (u_j) ↗			
REPELLING FIELD WIDTH (t_j)	OUTER-BANK: 30% OF ENCLOSURE WIDTH INNER-BANK: 40% OF ENCLOSURE WIDTH	OUTER-BANK: 20% OF ENCLOSURE WIDTH INNER-BANK: 40% OF ENCLOSURE WIDTH	30% OF ENCLOSURE WIDTH
(E)	OUTER-BANK: E = 0.1 INNER-BANK: E = 1.0	OUTER-BANK: E = 0.1 INNER-BANK: E = 0.0	E = 0.1

EXAMPLE K_j's for $t_j = 20$, $d_{ABORT} = 0$, $V_j = V_e = 1$

$$K_j = V_j V_e \left[1 - \left(\frac{d_j - d_{ABORT}}{t_j} \right)^E \right]$$



Note: If a goal or *fixed*-trajectory task is specified within primitive, the attractive pole is disabled and repelling-angles are set to 90 degrees.