Designing robot autonomy: how tightly should we hold the leash?

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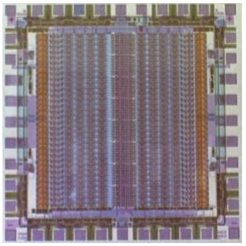
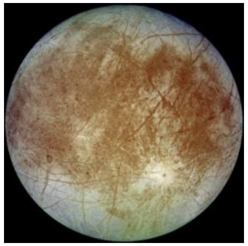
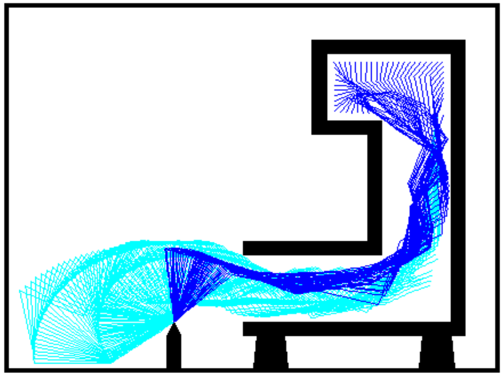
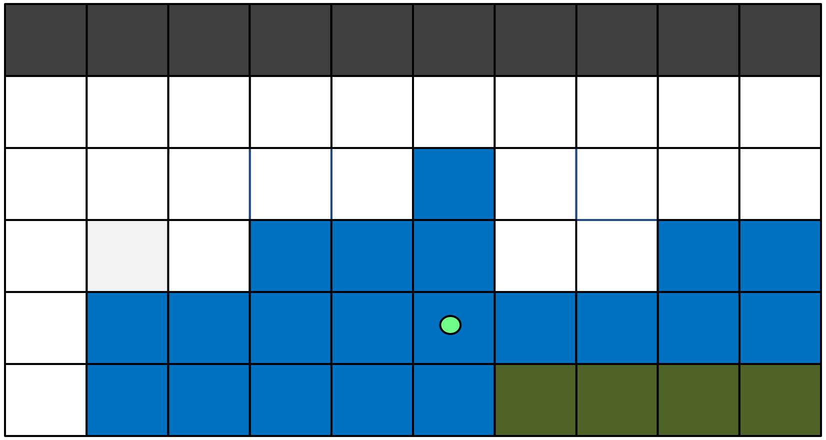






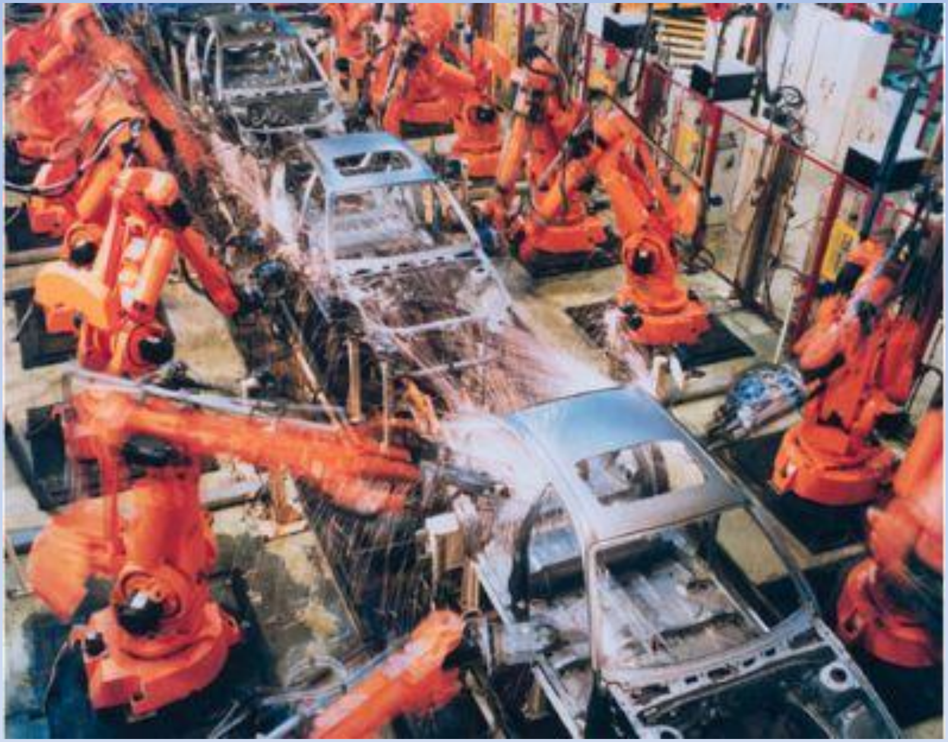


AGENDA
Designing Robot Autonomy for:

- Tedious or high-precision tasks
- Cleaning
- Search and rescue
- Super-human response
- Exploration ***(majority of talk)***
- Assisting the disabled
- Assistants/Companions

INDUSTRIAL ASSEMBLY

- Robots provide precision, repeatability, and strength

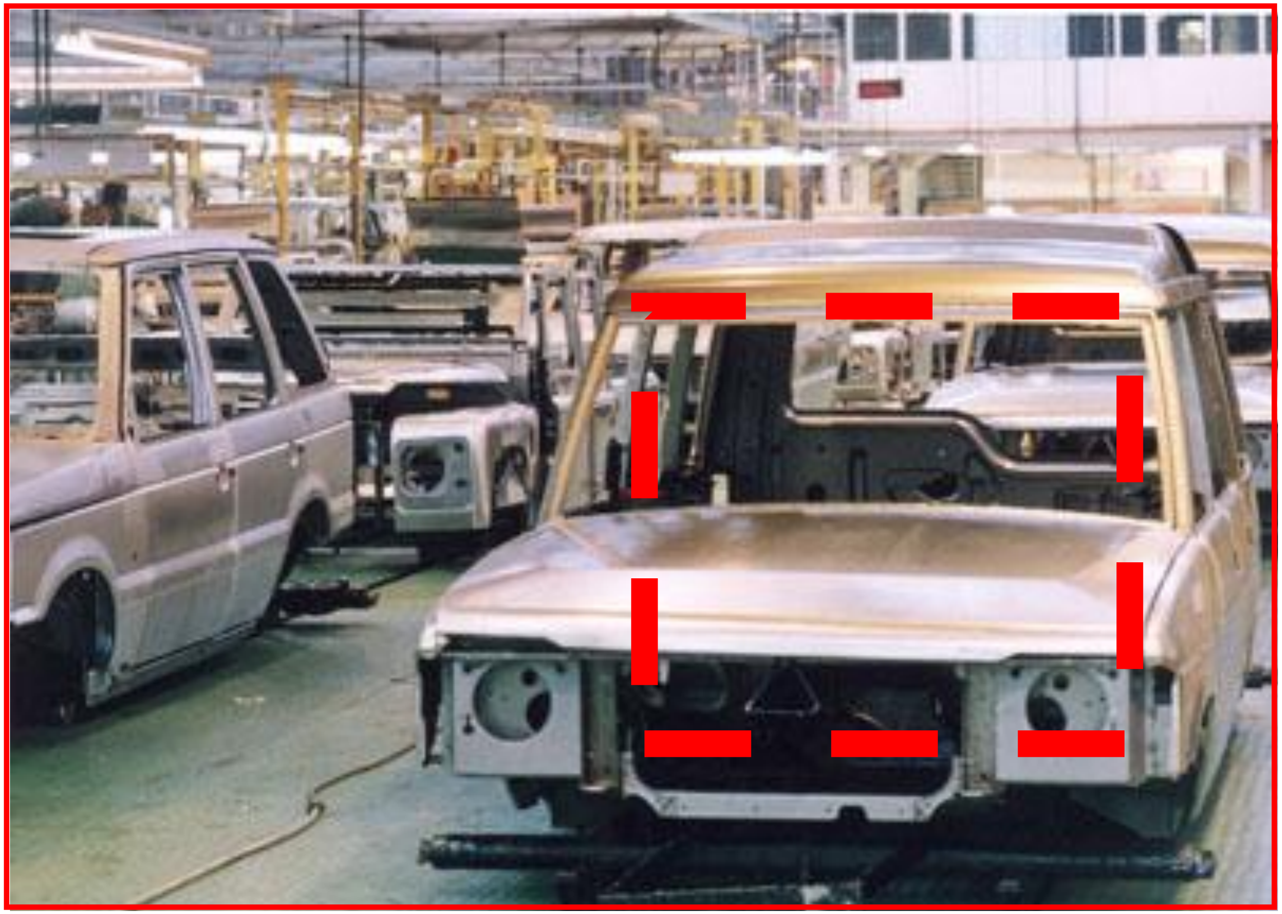


Autonomy Risks: Worker safety; Damaged materials

Mitigation: Limit velocity, torque, and motion-range; Caged restricted work-cells

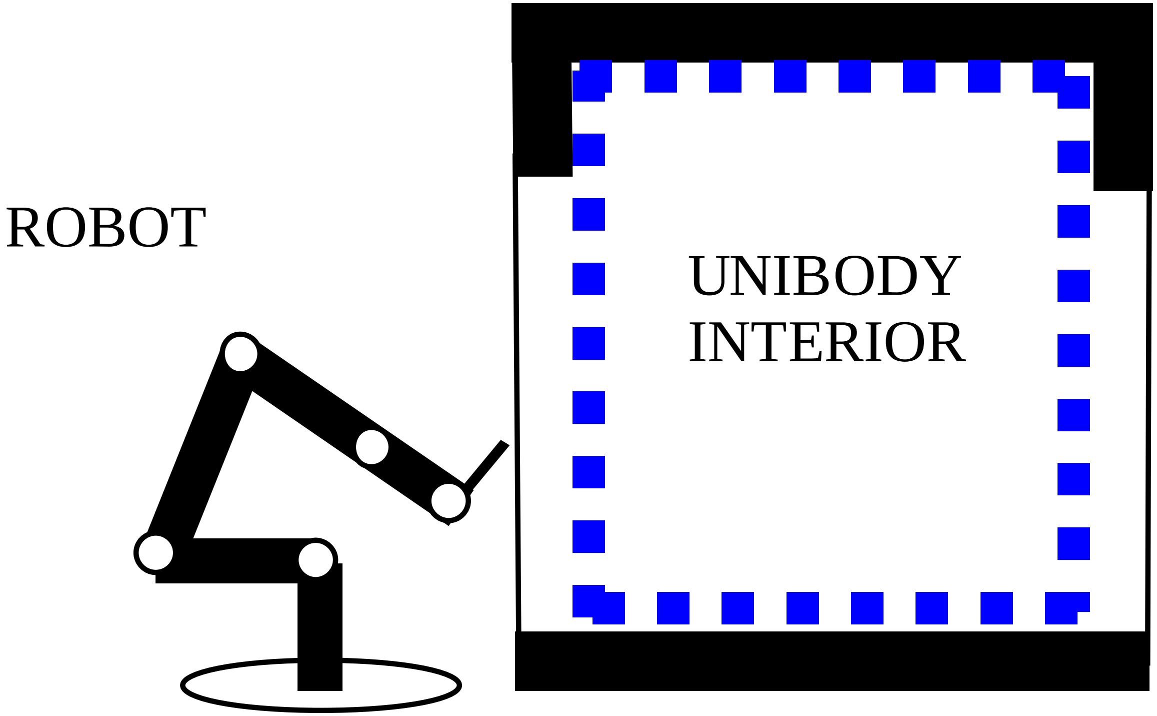
Image from: http://www.robot-welding.com/

Example Welding Task



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.

Example Welding Task



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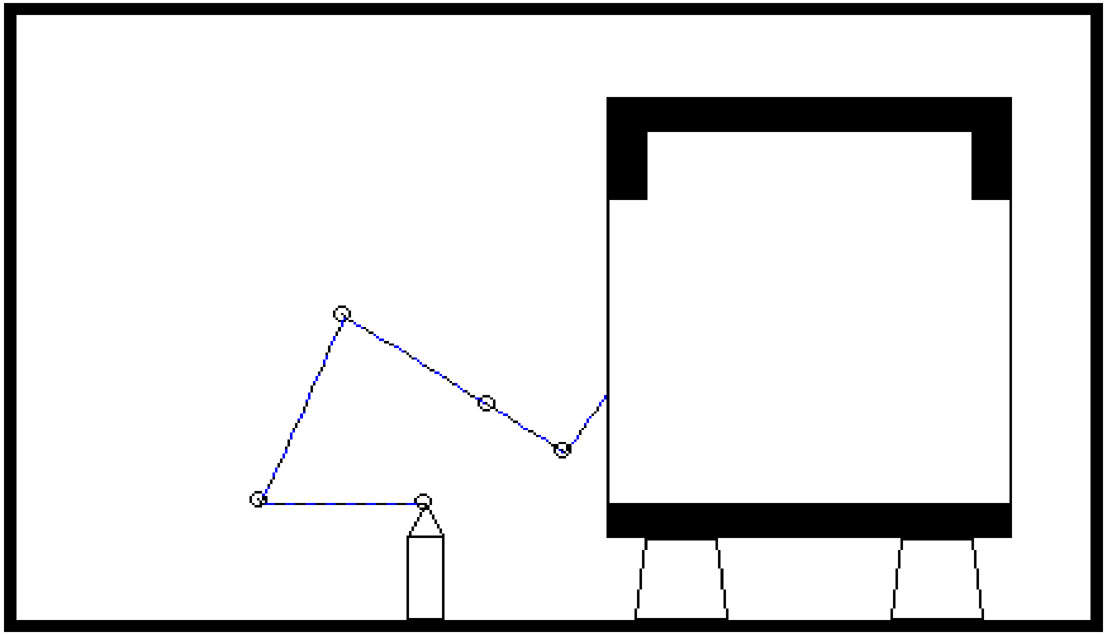
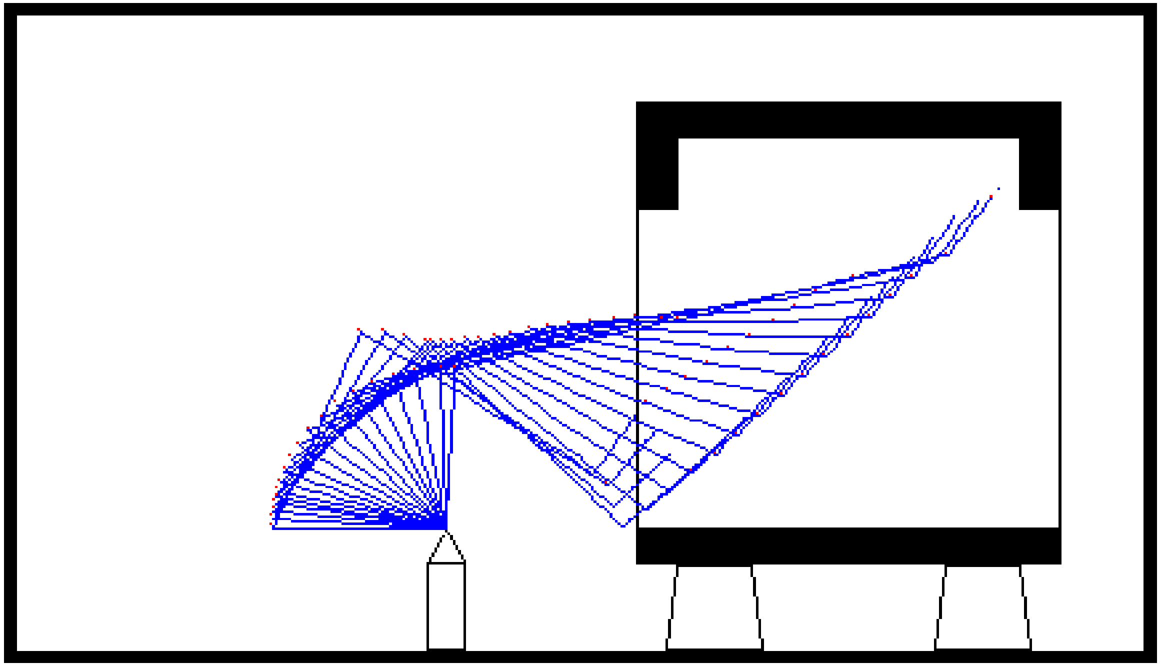
Simulation (initialization)



Research to find robotic arm designs for enclosed spaces, with optimization of velocities, maniplulability, singularity-avoidance, and degrees of freedom

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.

Simulation (go to task start-point)



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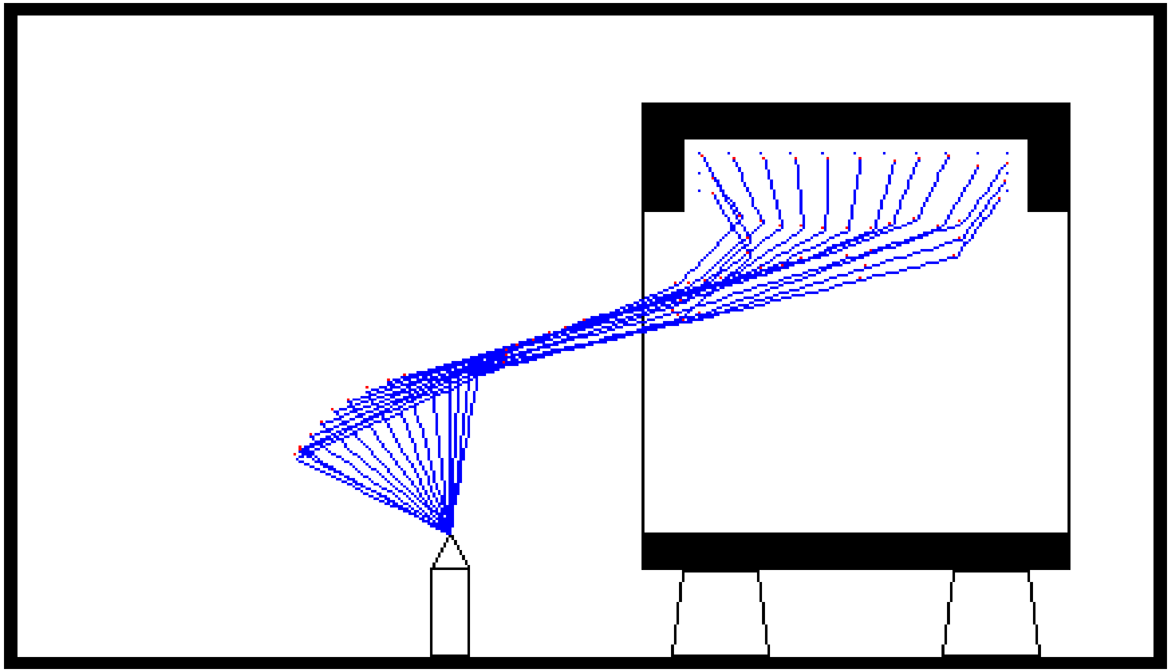
Simulation (perform welding task)



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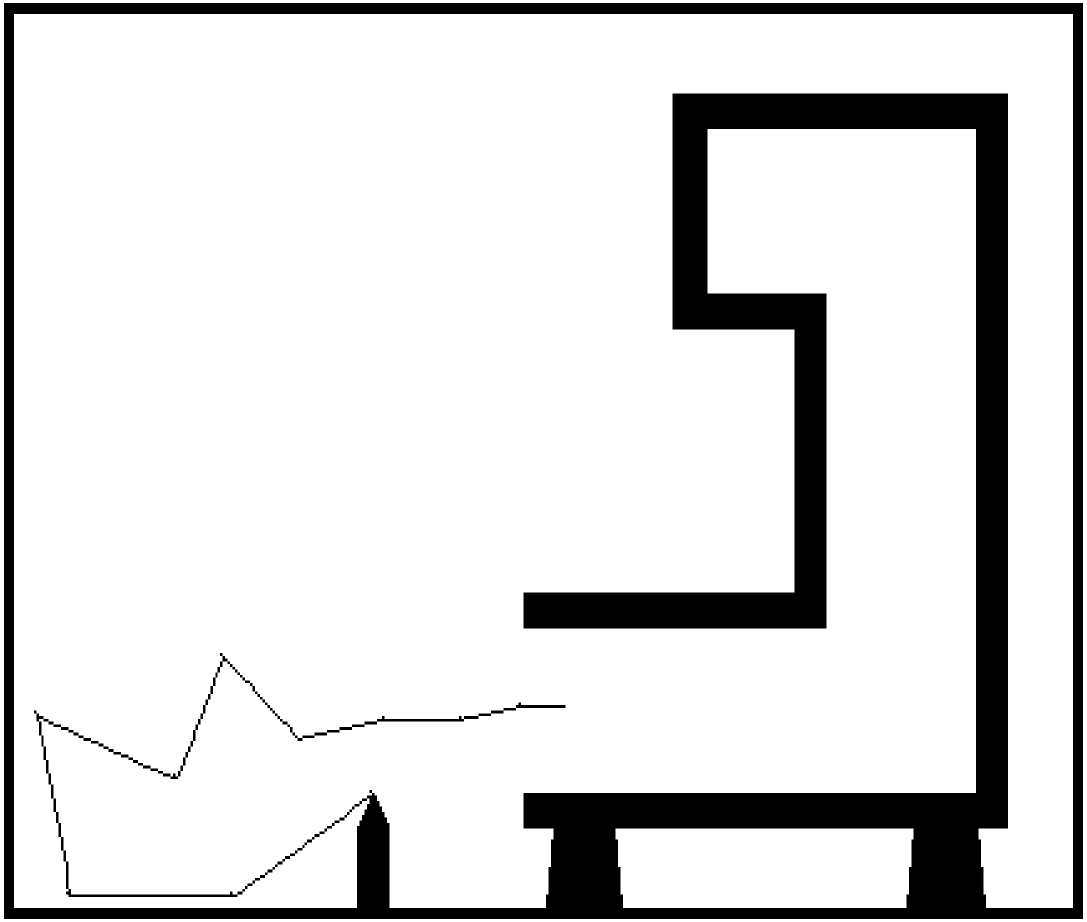

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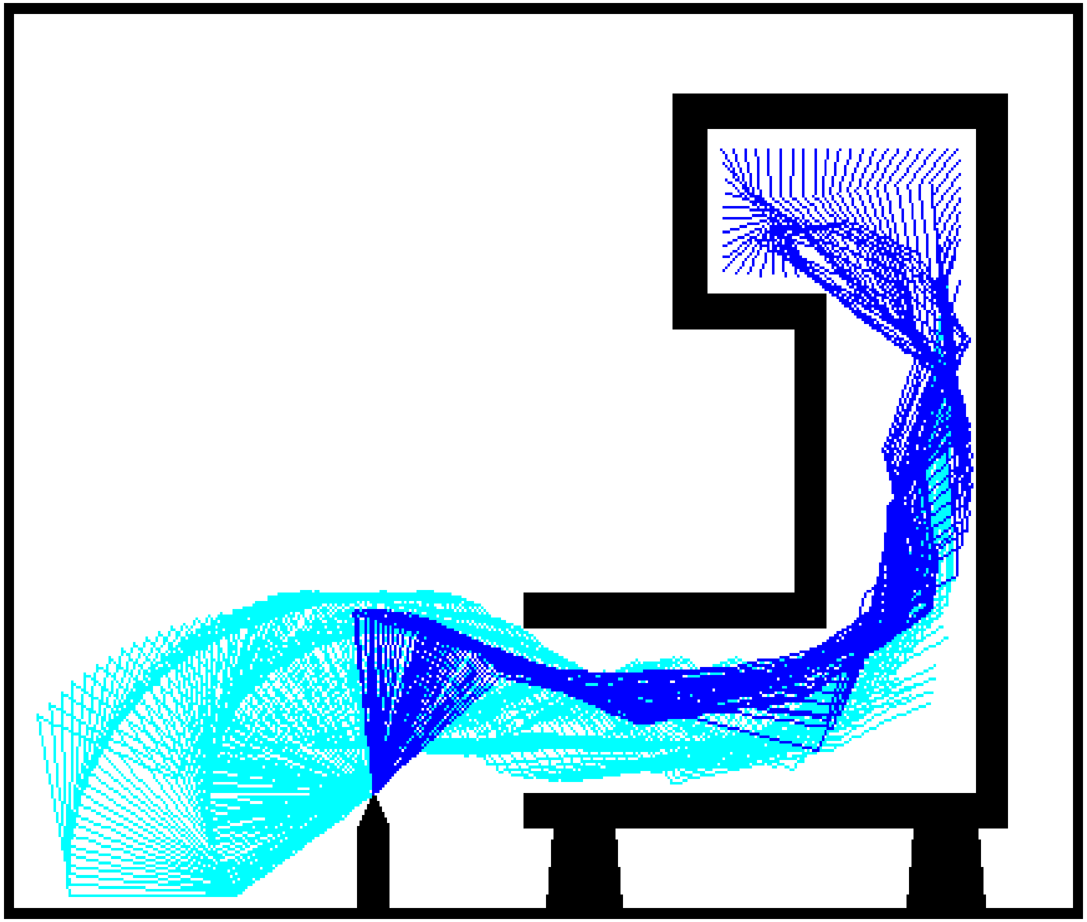

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ROBOTIC SURGERY

- Robot filters out shakiness of surgeon's hands

Autonomy Risks: Patient safety

Mitigation: Limit velocity, torque, and motion-range; No automated procedures

Image from: http://www.durhamregional.org/services/surgery/da_vinci

CLEAN-UP

- Robots don't get sick from contamination

It excretes large ice cubes

Autonomy Risks: Injuries to people; Property damage

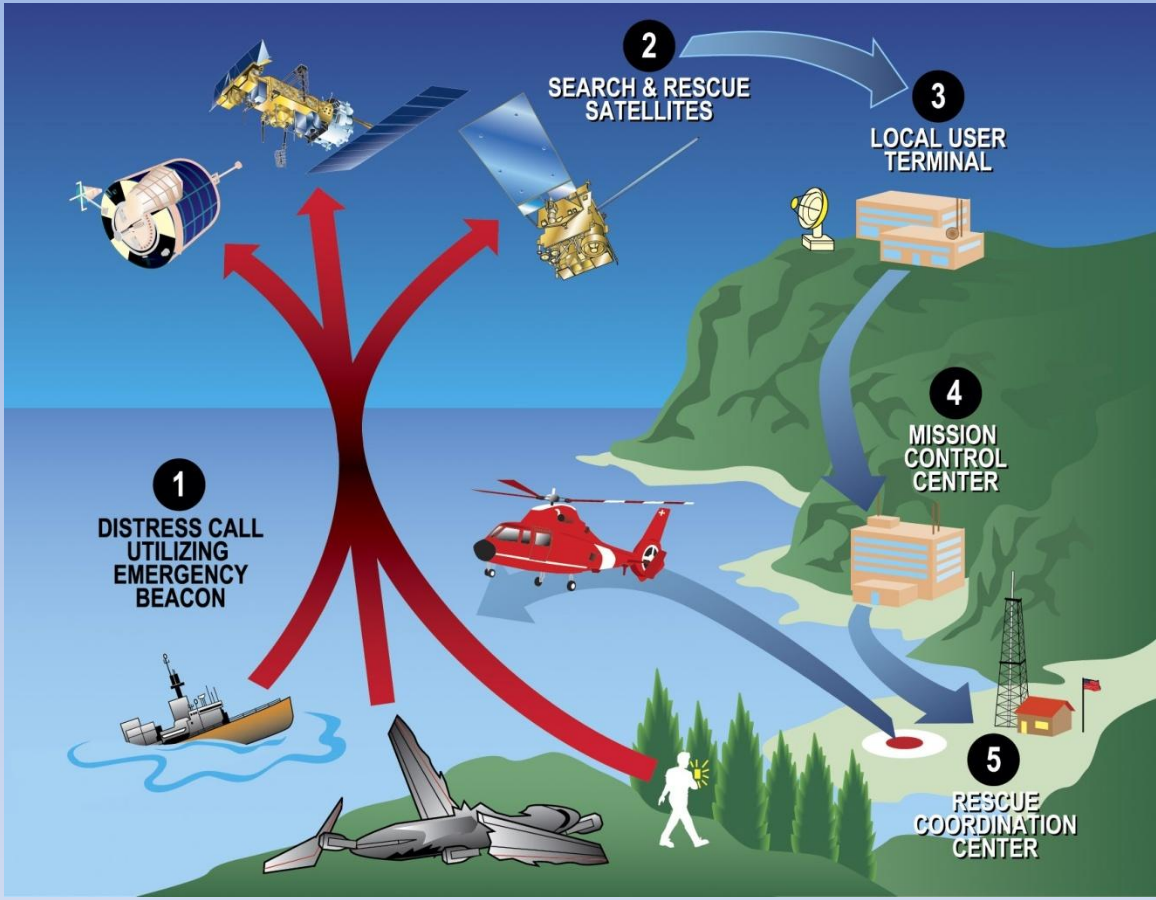
Mitigation: Limit velocity and power; Obstacle avoidance hardware & software

Image from: http://dvice.com/archives/2007/02/roombalike_snowplow_robot_uses.php

Image from: http://www.robotvacuumcleaner.org/2009/09/roomba-pet-series-532-and-562-features

SEARCH AND RESCUE

- Robots prevent responders from being injured



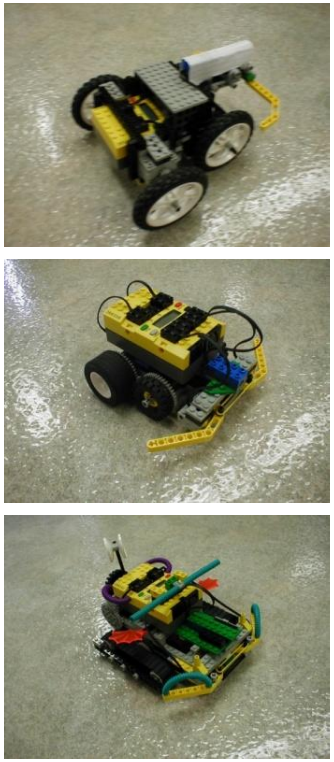
Autonomy Risks: Safety of those being rescued

Mitigation: Minimize robot manipulation of those being rescued; Always have a human in control and fully aware of robot's actions via tele-robotic control

Image from: : http://www.wired.com/science/discoveries/news/2001/09/46930

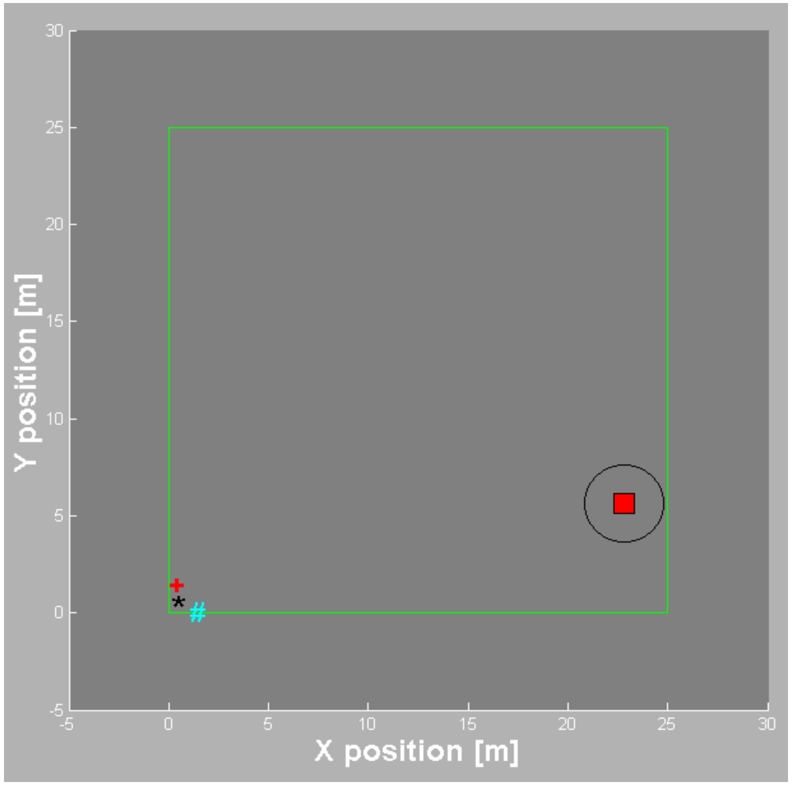
Image from: : http://www.semp.us/publications/securitas_reader.php?SecuritasID=33

SEARCH AND RESCUE



Real-time Robots

(programmed in C and Visual Basic)



Simulation

(programmed in Matlab)

Scout (black *)
Medic (blue #)
Fire-suppressant (red +)

Goal (red sqaure)

Campos, D. and Wunderlich, J. T. (2002). **Development of an interactive simulation with real-time robots for search and rescue**. In *Proceedings of IEEE/ASME International conference on Flexible Automation, Hiroshima, **Japan***: (session U-007). ASME Press.

MILITARY AND POLICE

- Robots protects soldiers and police

Recommended Reading: ["Governing Lethal Behavior in Autonomous Robots"]() by Ronald Arkin

Autonomy Risks: Brutality, Geneva Convention violations

Mitigation: Minimize weaponization; Always have human in control of robot (and fully aware of situation). Ensure operator has an ethical sense of *"rules of engagement"*

Image from: http://lifescience.com
Image from: http://lemonodor.com/archives/001214.html
Image from: http://nextbigfuture.com/2009/03/military-robots-can-follow-hand-signals.html

EXPLORATION

- Robots protect explorers from remote dangers
- OK to leave a robot in a distant place
  (retrieving human astronauts is very expensive)

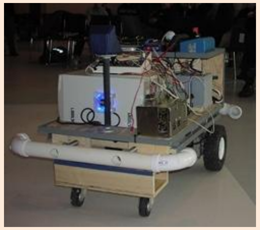
Some of my students with one of our Robots

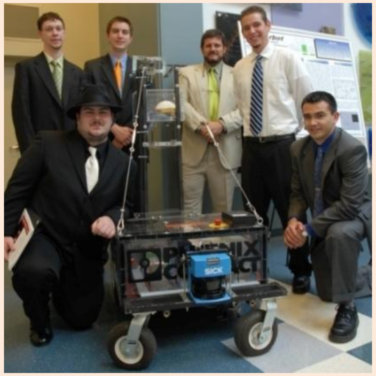
Autonomy Risks: Very expensive robots destroyed

Mitigation: Ensure high-quality autonomy programming

Autonomy in Rovers

1999 to 2011 Our autonomous “***Wunderbots***”





1996-2016 Mars semi-autonomous rovers

1996: NASA Pathfinder ***“Sojourner”***

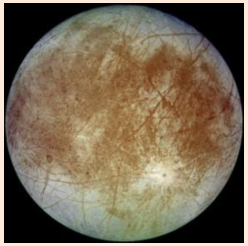
2004: NASA ***“Spirit”*** & ***“Opportunity”***

2011: NASA Mars Science Lab ***“Curiosity”***

2016: ESA ***“ExoMars”***

2020 ESA/NASA ***“Europa Jupiter System Mission”***

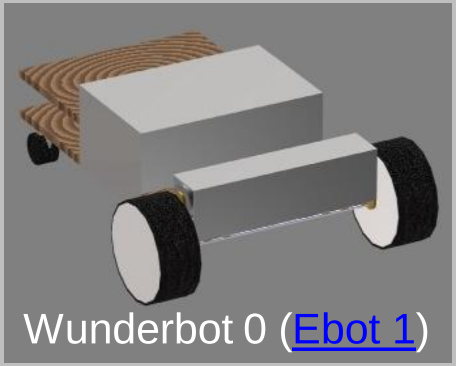
- No rover planned for this mission
- Academic project for Fully Autonomous Europa Rover (for **~2040**)
  - *University of Trento Italy Ph.D. course* optional course paper
  - *2011 Elizabethtown College course project*

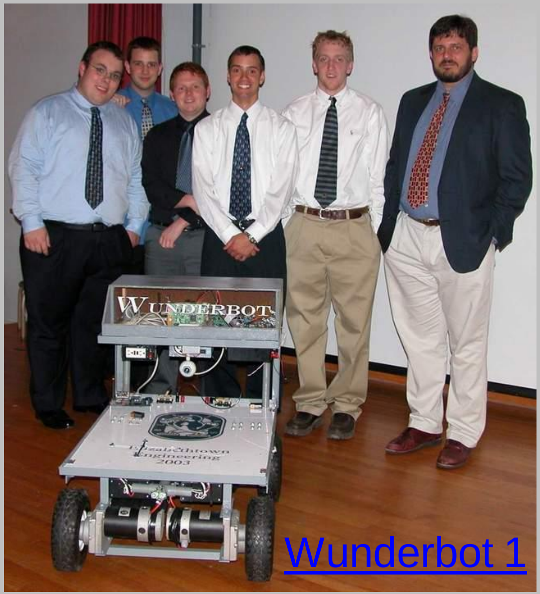


Our AUTONOMOUS Robots since 1999

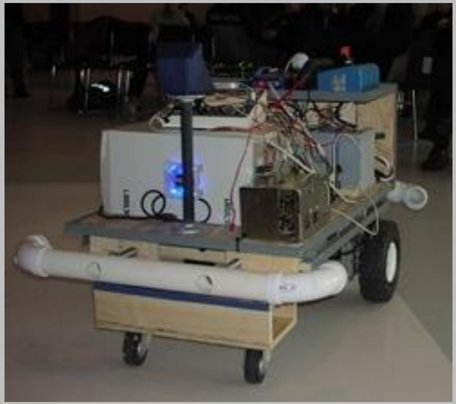
Wunderbot 2, 3, and 4 subsystems:

- 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


Wunderbot 0 (Ebot 1)



Wunderbot 1


Wunderbot 2 prototype


Wunderbot 2

Wunderbot 3

Wunderbot 4

Our AUTONOMOUS Robots since 1999

Recent goal of wunderbots is

[IGVC (Intelligent Ground Vehicle Competition)]

~50 competing Universities (some International)

TWO OBSTACLE COURSES:

(1) Quickly visit 10 GPS points while avoiding barrels, fencing, and white-line boundaries

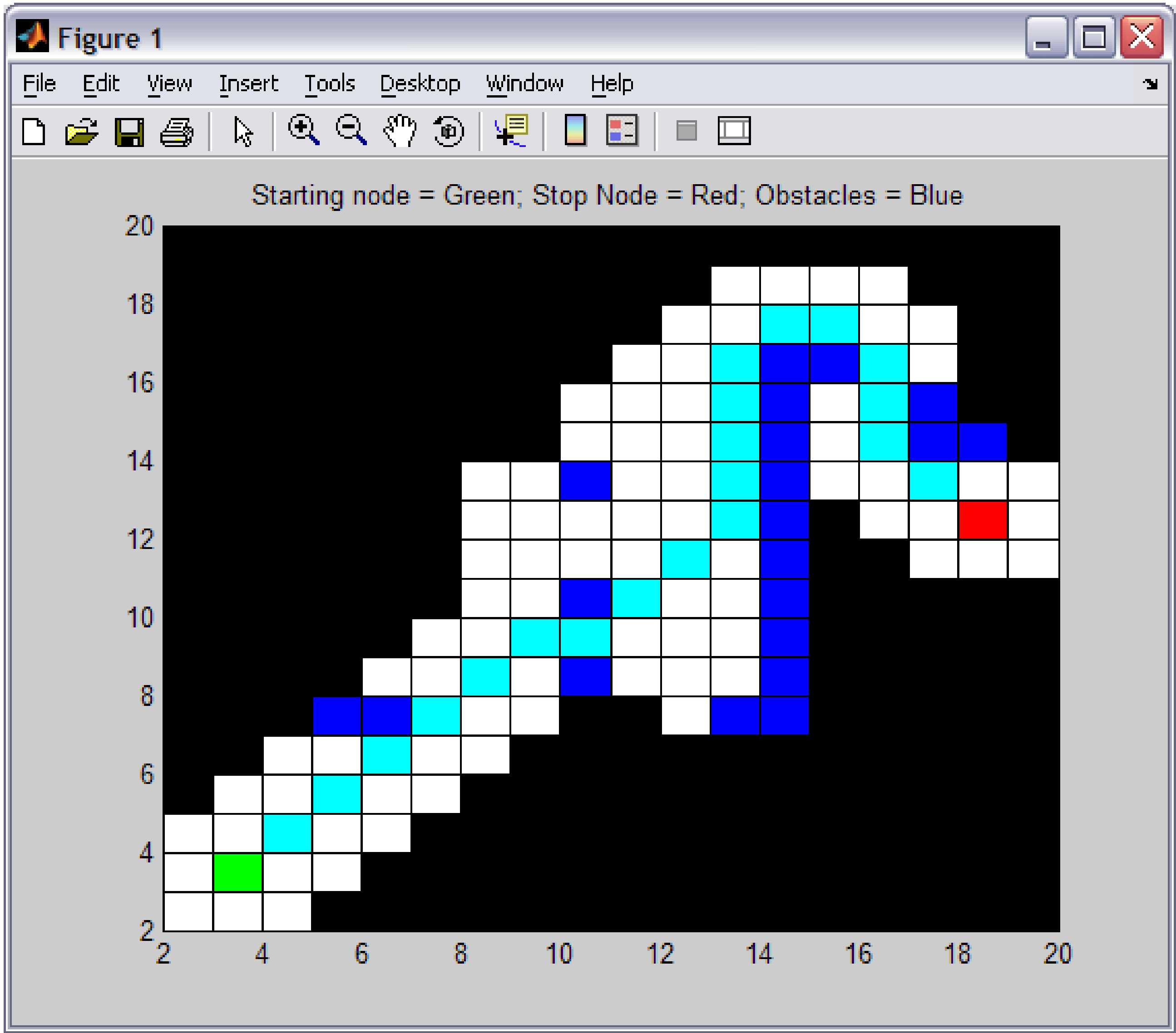
(2) Navigate a course defined by white lines while avoiding barrels, fencing, and blockades:

NEED FULL AUTONOMY !

- No tele-operation allowed !!

Wunderbot 4
LOCAL Path-Planner

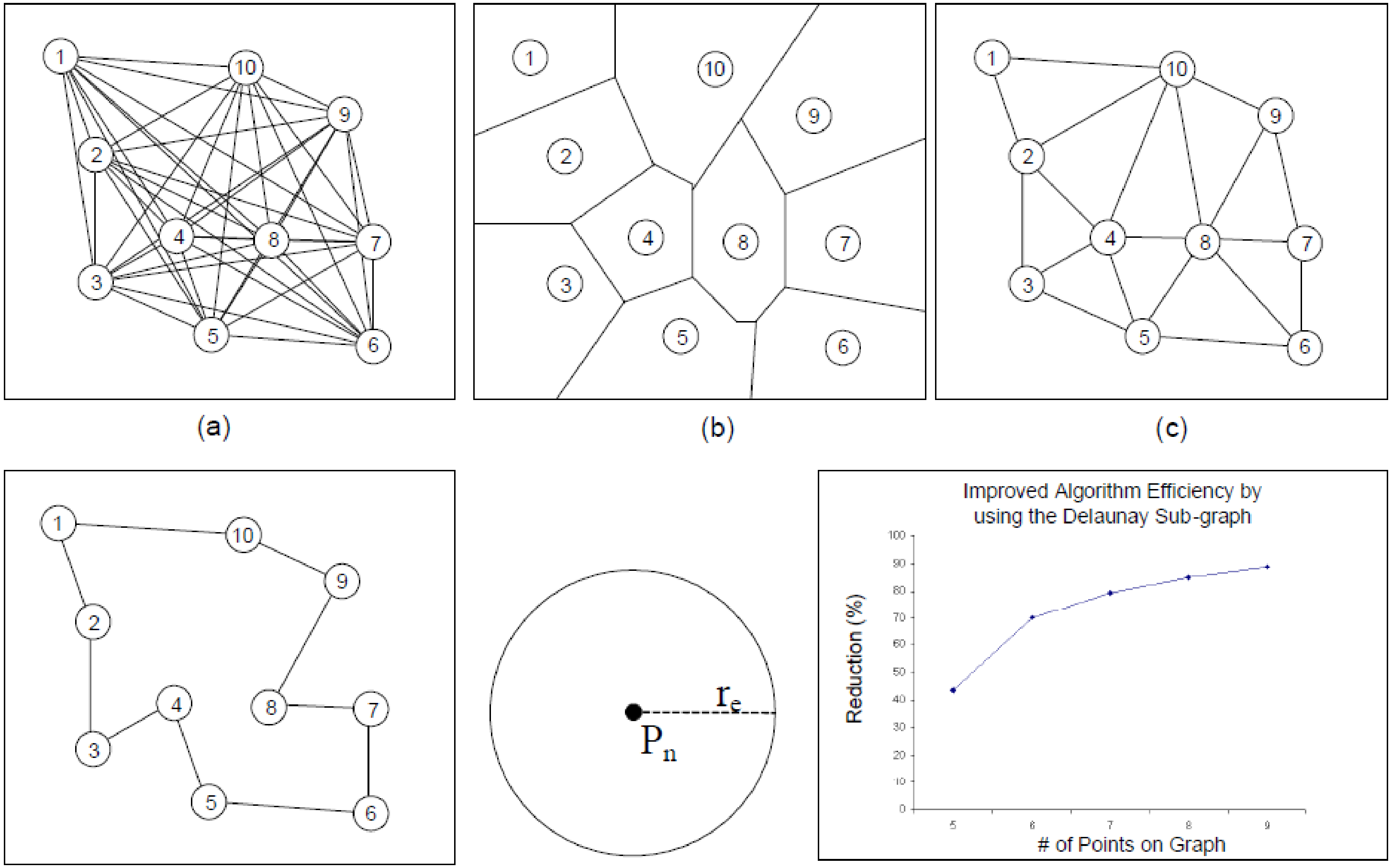
PRELIMINARY RESEARCH
by David Colman *(advisor: J. Wunderlich)*



Starting node = Green; Stop Node = Red; Obstacles = Blue

Wunderbot 4
GLOBAL Path-Planner

by David Colman (Advisor: J. Wunderlich)



(a) (b) (c)

(d) (e) (f)

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). **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 also Opportunistic

by David Colman *(Advisor: J. Wunderlich)*

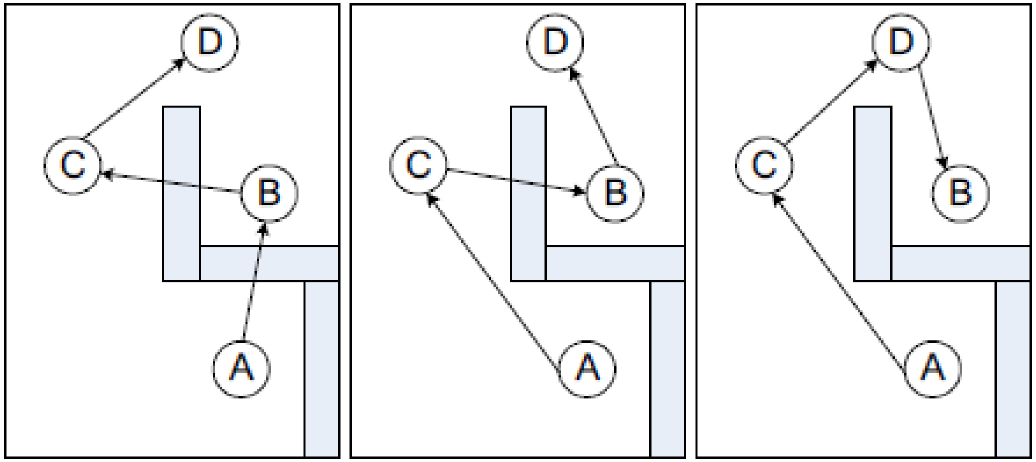


Fig. 6. Map with more than one point of opportunity. The original TSP dictates an A-B-C-D path. After the γ analysis, A-C-D-B is locally opportunistic and globally optimal.

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
LADAR and Vision

Vision by James Painter (advisor: J. Wunderlich)

Newer Vision by Mike Conlow and Aung Than (advisor: J. Wunderlich)

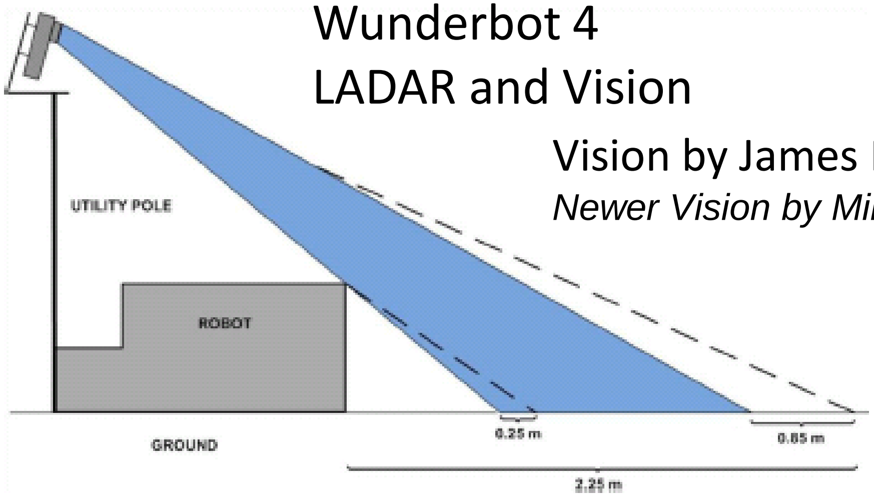
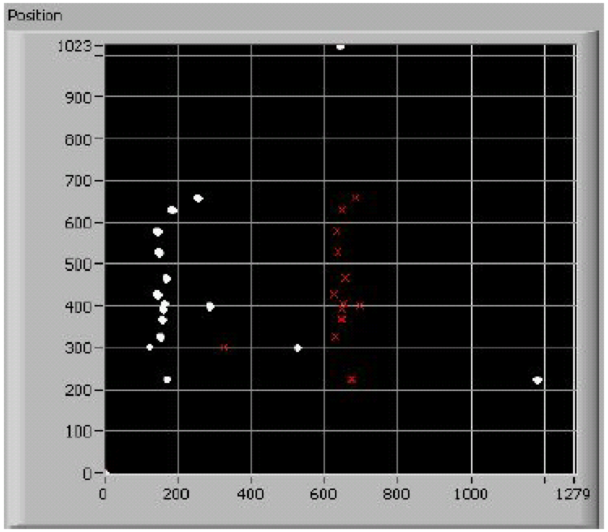


Fig. 2. Camera viewable region, with camera mounted directly above rear bumper (blue fill) and with camera shifted back 40.5cm from rear bumper (dashed lines).

(a) (b)

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



(a)

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

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

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

Wunderbot 4
Wireless Communication
by Jeremy Crouse *(advisor: J. Wunderlich)*

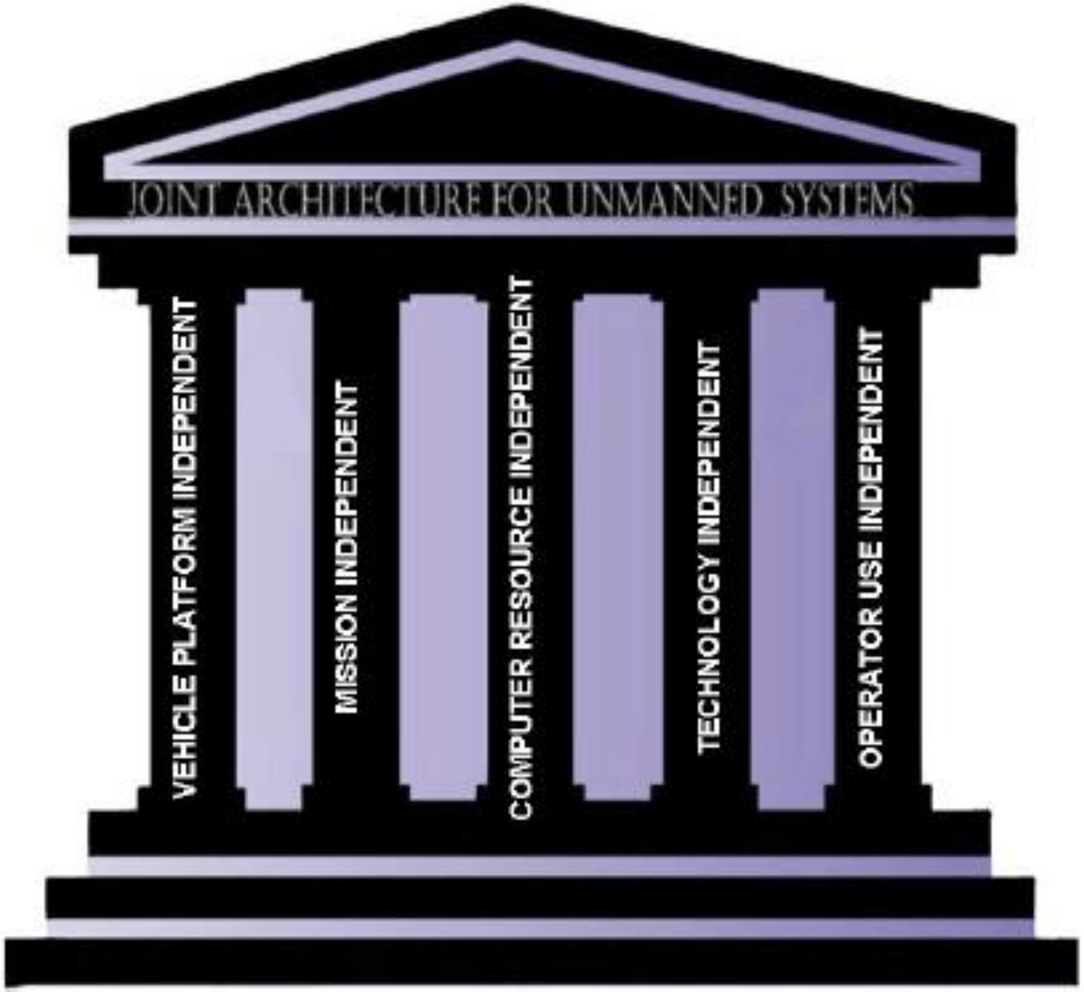


Figure 1: JAUS Independence requirements [3]

Although full autonomy required, the IGVC awards those who can respond to “JAUS”

We were one of only a few to win this in 2008

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

Wunderbot 4
Systems Integration (and Sensor Fusion)

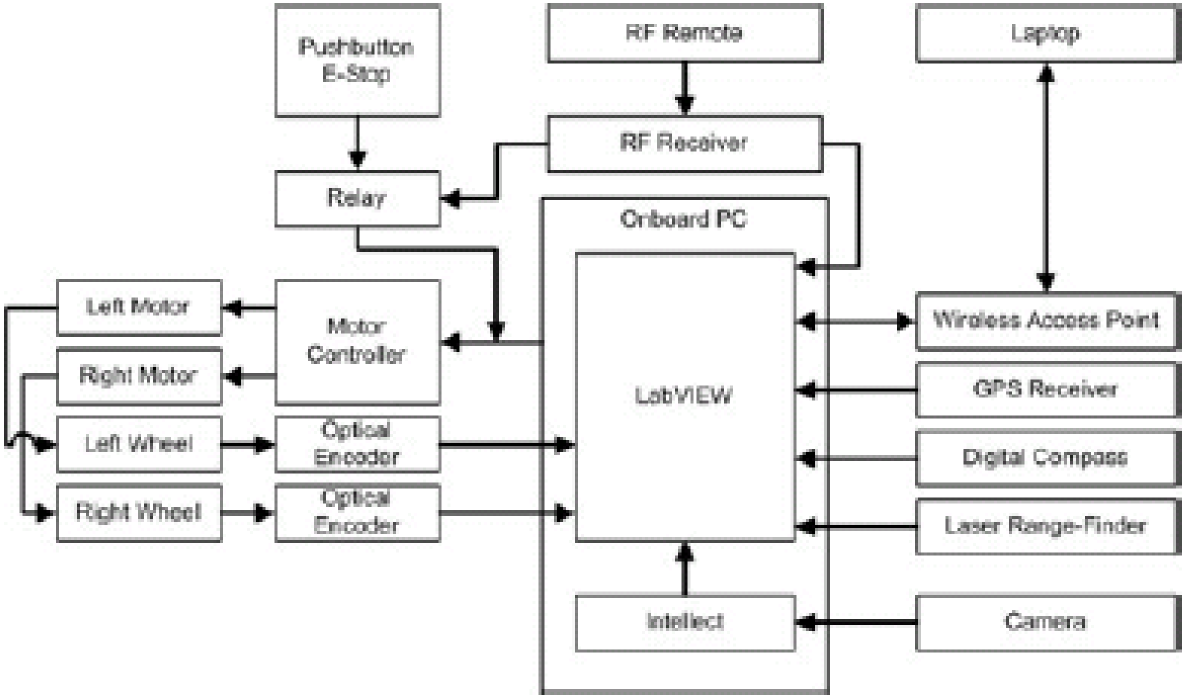


Fig. 8. Block diagram of Wunderbot IV subsystems.

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

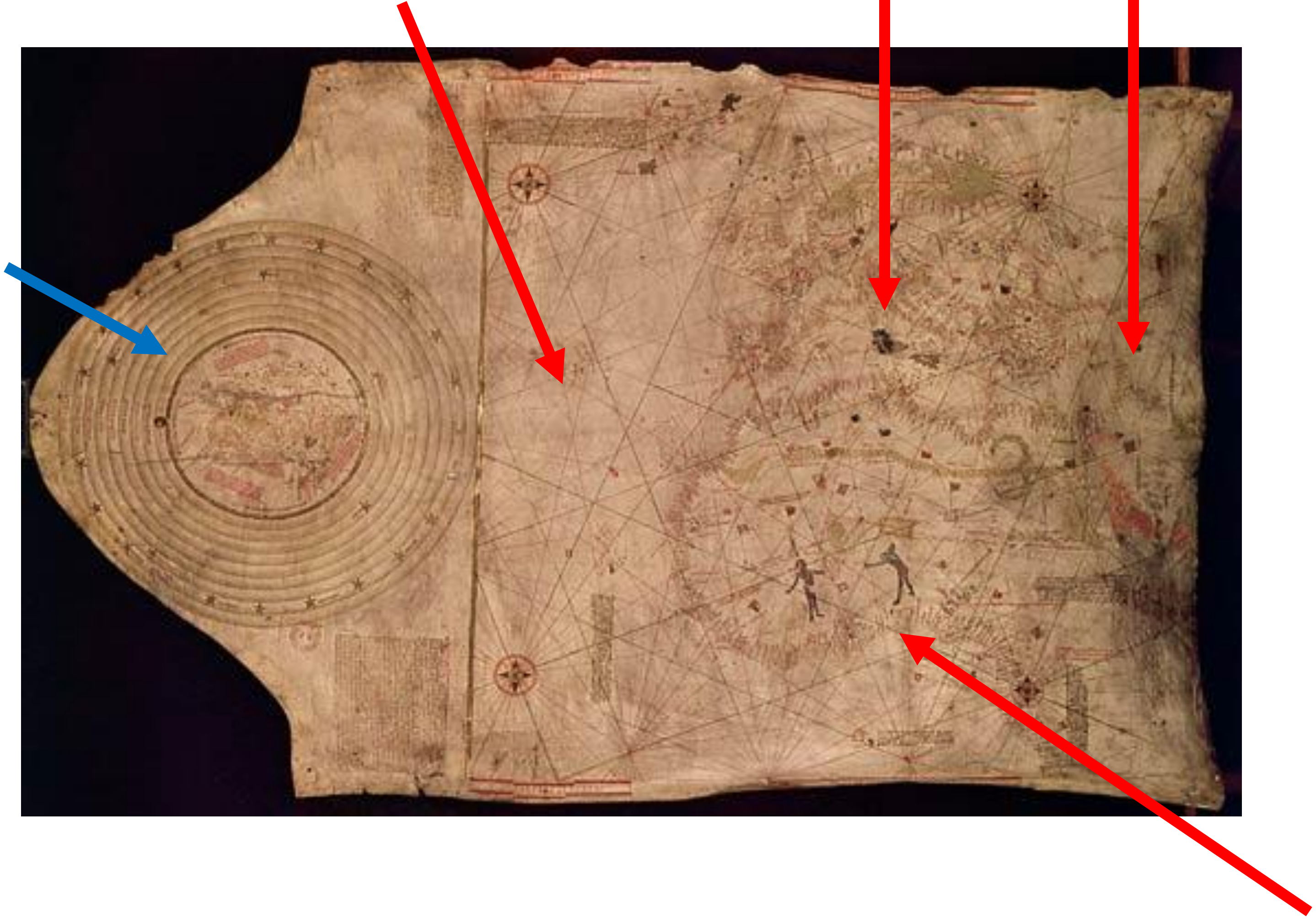

IGVC
IGVC

Wunderbot now being re-tooled for Environmental Sampling

- Integration with other environmental initiatives on campus
- Robotic Arm being added for environmental sampling

Some Exploration Fundamentals

Christopher Columbus's map



One ocean
(Atlantic and Pacific)

Europe

Asia

Earth with planets orbiting it

Africa

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

Exploration Fundamentals

DEAD RECKONING

Find **Position and Orientation (“POSE**”):

1) Measure HEADING with compass

2) Measure TIME TRAVELED

3) SPEED calculated by measuring time for debris to float between marks on ship’s side

4) DISTANCE TRAVELED =
SPEED x TIME TRAVELED

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

CELESTIAL NAVIGATION

Polaris doesn’t *move* across night sky since Earth’s axis points directly at it

Google Earth to see 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

VIDEO: http://www.youtube.com/watch?v=RDRGwsSeOwA

Exploration Fundamentals

"Pose Estimation" (position and orientation) is essential for AUTONOMY

Local path-planning *(like dead-reckoning)* doesn't guarantee optimal paths

Establishing a reference frame *(like with Celestial Navigation)* helps develop **Global path-planning**

Can combine local planning for obstacle avoidance with global planning

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

- Space is our *Final Frontier*

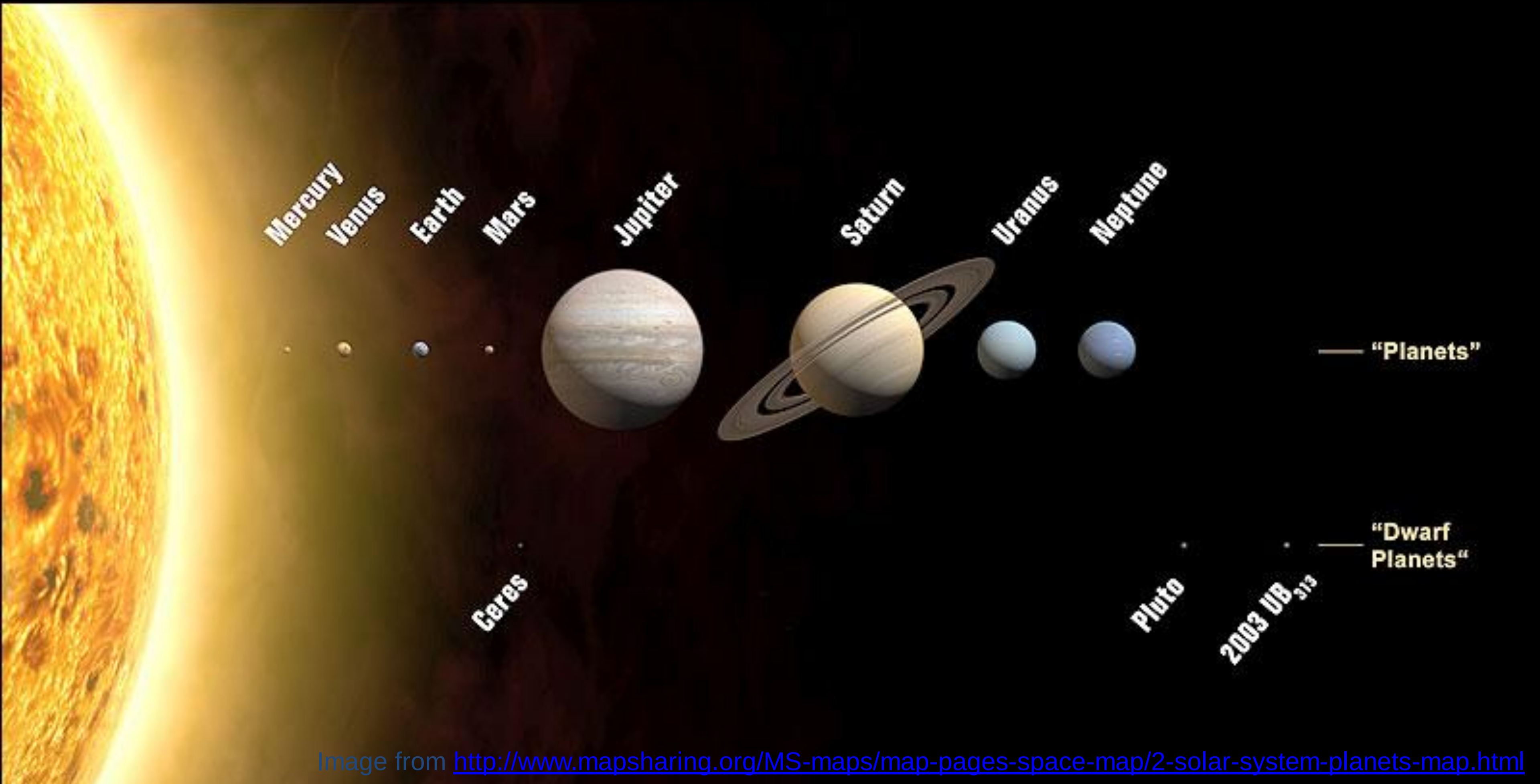


Image from http://www.mapsharing.org/MS-maps/map-pages-space-map/2-solar-system-planets-map.html

- Galaxies contain billions of stars
- We live in the *Milky Way* galaxy

Image from http://photojournal.jpl.nasa.gov/gallery/universe?start=0

and there are billions of galaxies !

EXPLORATION

Image from http://www.myspace.com/intelligentinfinity

Exploration limits

Our fastest space travel is 60,000KPH which is 20,000 times slower than the speed of light

Closest star (Alpha Centauri) is 4 light-years away

So fastest ship would need 65,000 years to get there

Closest galaxy is 80,000 light -years away, and would take 1 billion years to get there !

NOTE: One light-year = distance light travels in one year at 1 Billion KPH

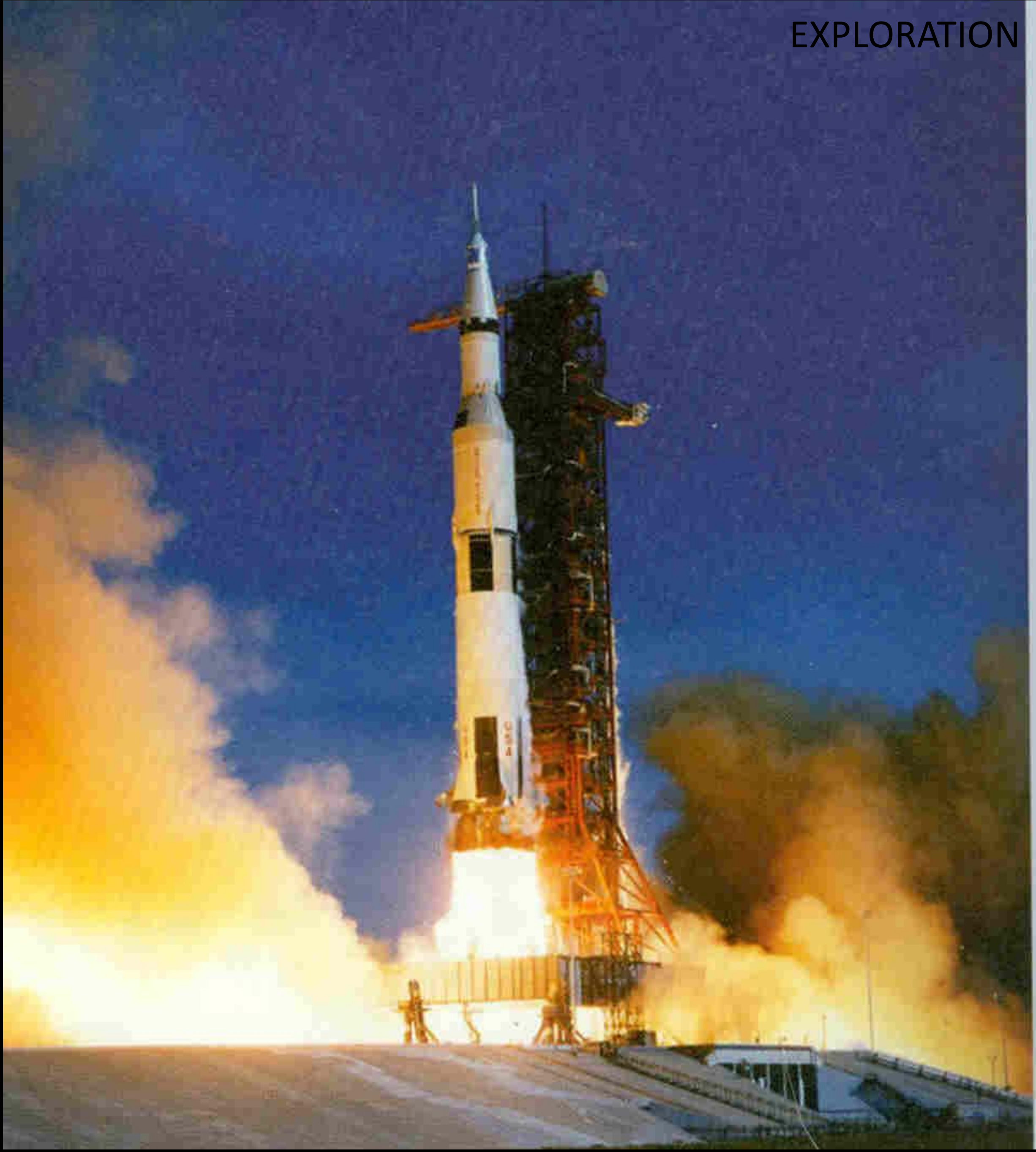


Image from: Young, A.H. ***Lunar and planetary rovers: the wheels of Apollo and the quest for mars***, Springer; 1 edition, August 1, 2006.

So although we can listen for signals from outside our solar system . . . .

Image from http://abscicon.seti.org/index.php we will likely never travel far outside our solar system …………..

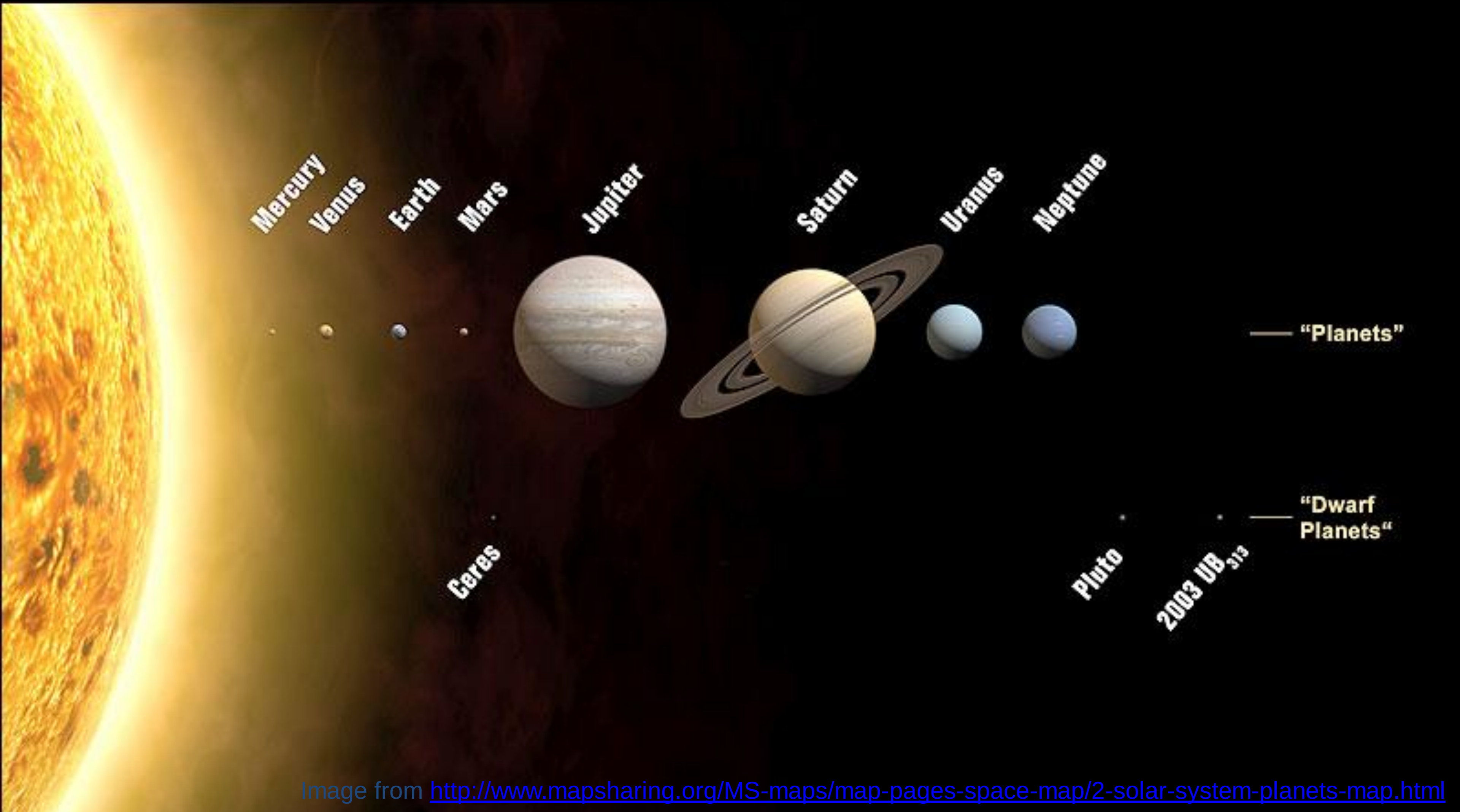


Image from http://www.mapsharing.org/MS-maps/map-pages-space-map/2-solar-system-planets-map.html

.. at least not manned missions

Unmanned Space-craft locations as of May 24, 2009

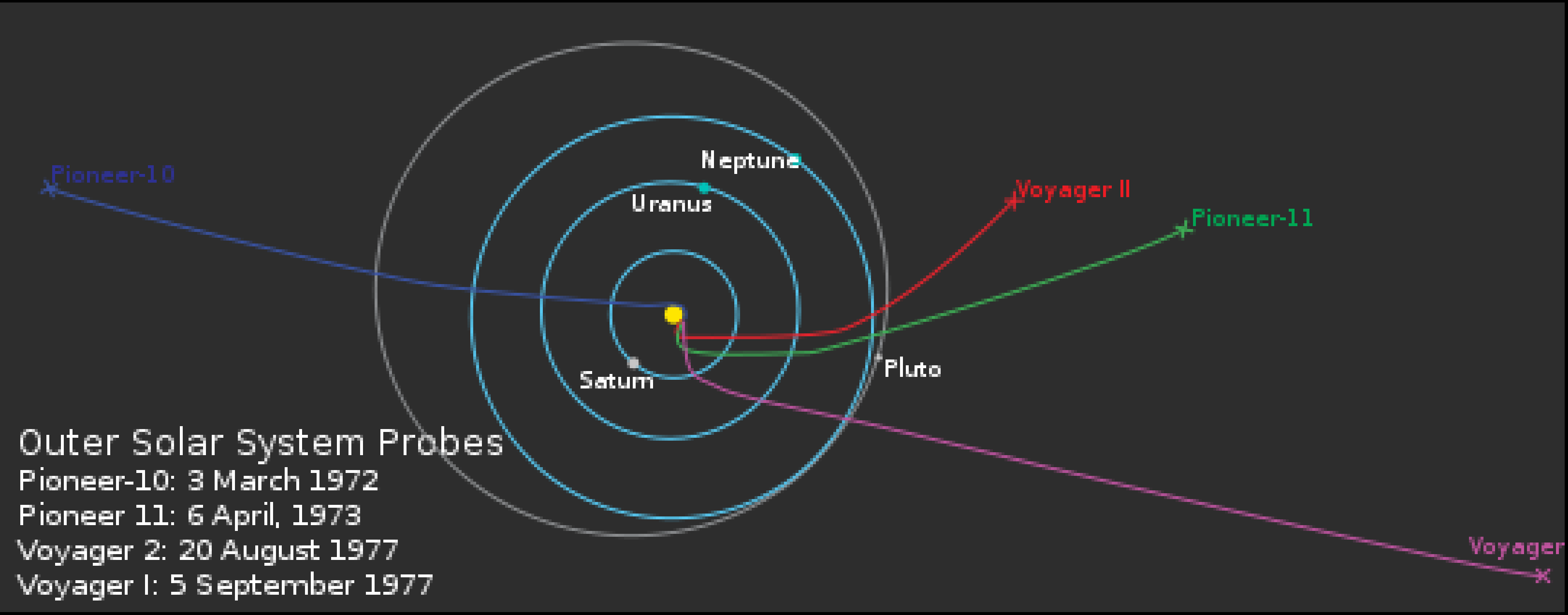


Image from: http://en.wikipedia.org/wiki/Voyager_1

However there is much left to explore in our solar system ….

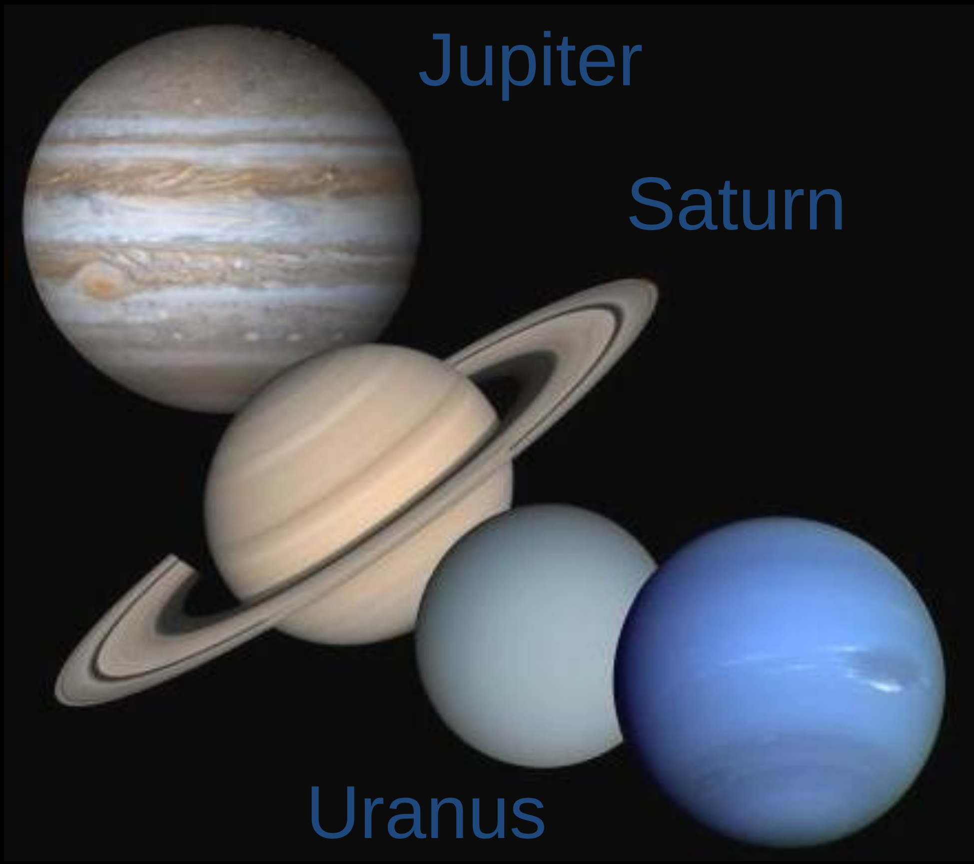


Image from http://www.eso.org/public/outreach/eduoff/vt-2004/Background/Infol2/EIS-D4_pf.html

Image from http://astrophys-assist.com/educate/robot/page11.htm

And many moons to explore ……..

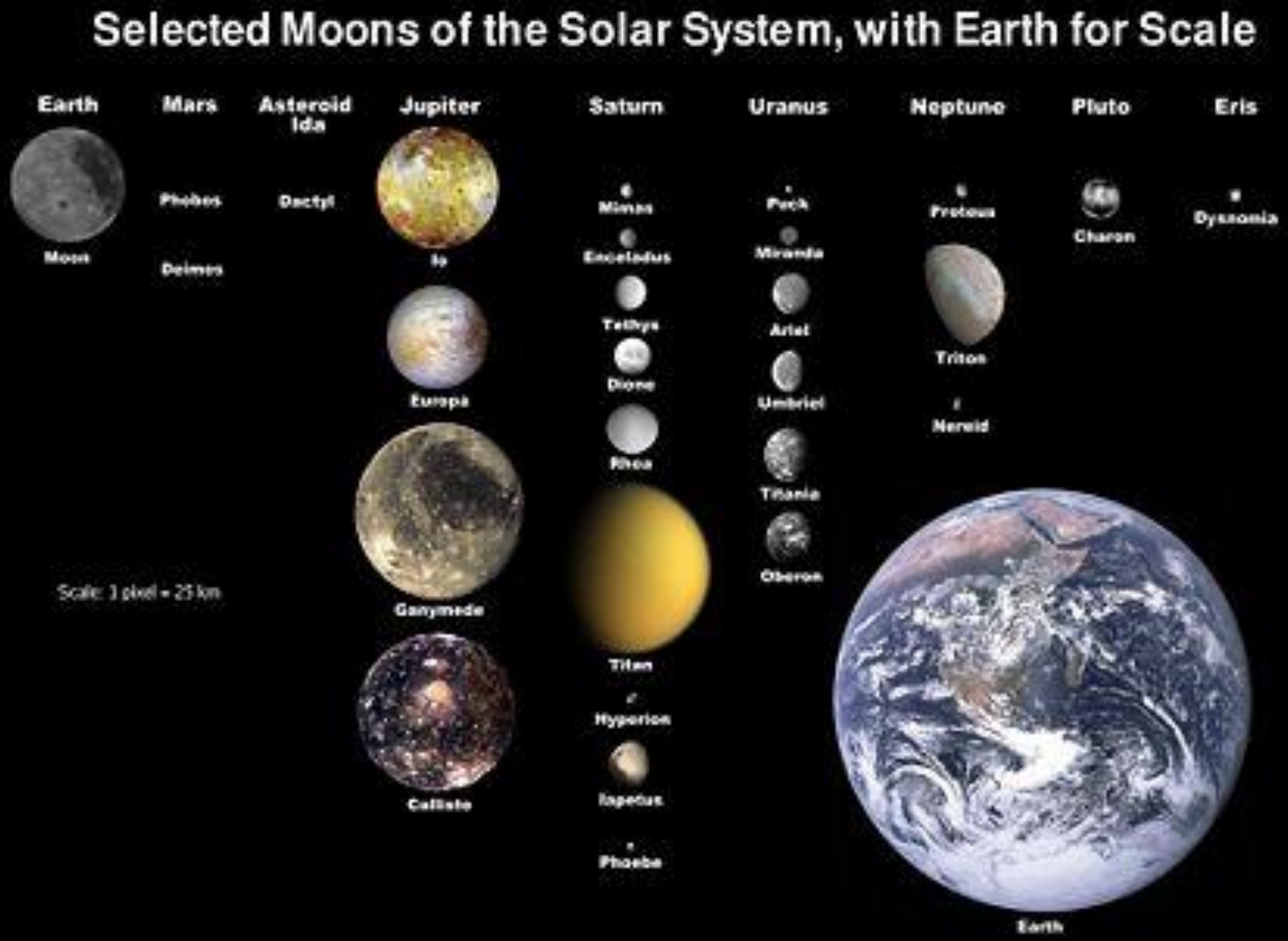


Image from http://www.factmonster.com/spot/solar-system.html

Semi-Autonomous tele-operated robots react very slowly when waiting for commands from Earth
(up to 26 minutes for signals to reach Mars)

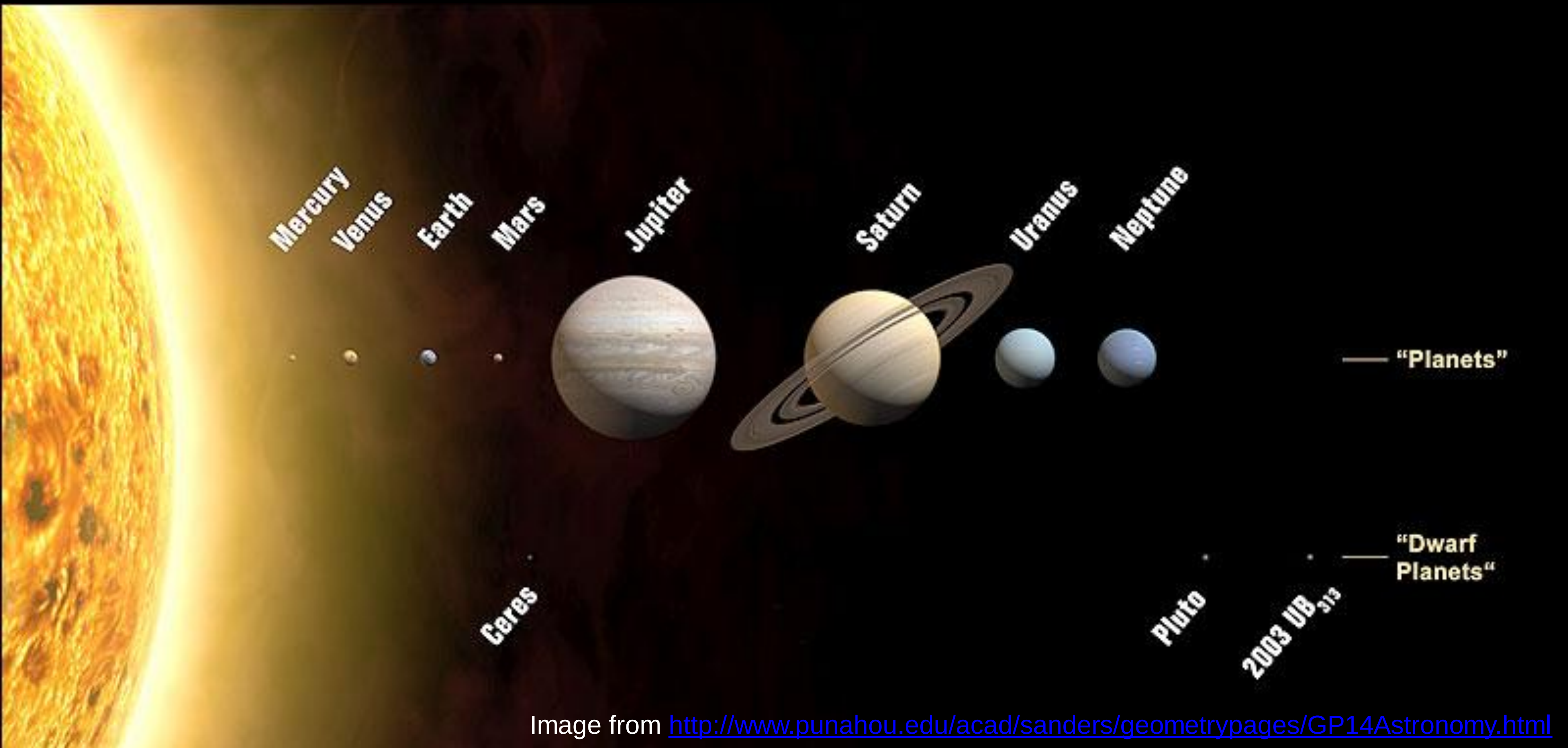


Image from http://www.punahou.edu/acad/sanders/geometrypages/GP14Astronomy.html

So tele-operated robots at great distances need maximum AUTONOMY !

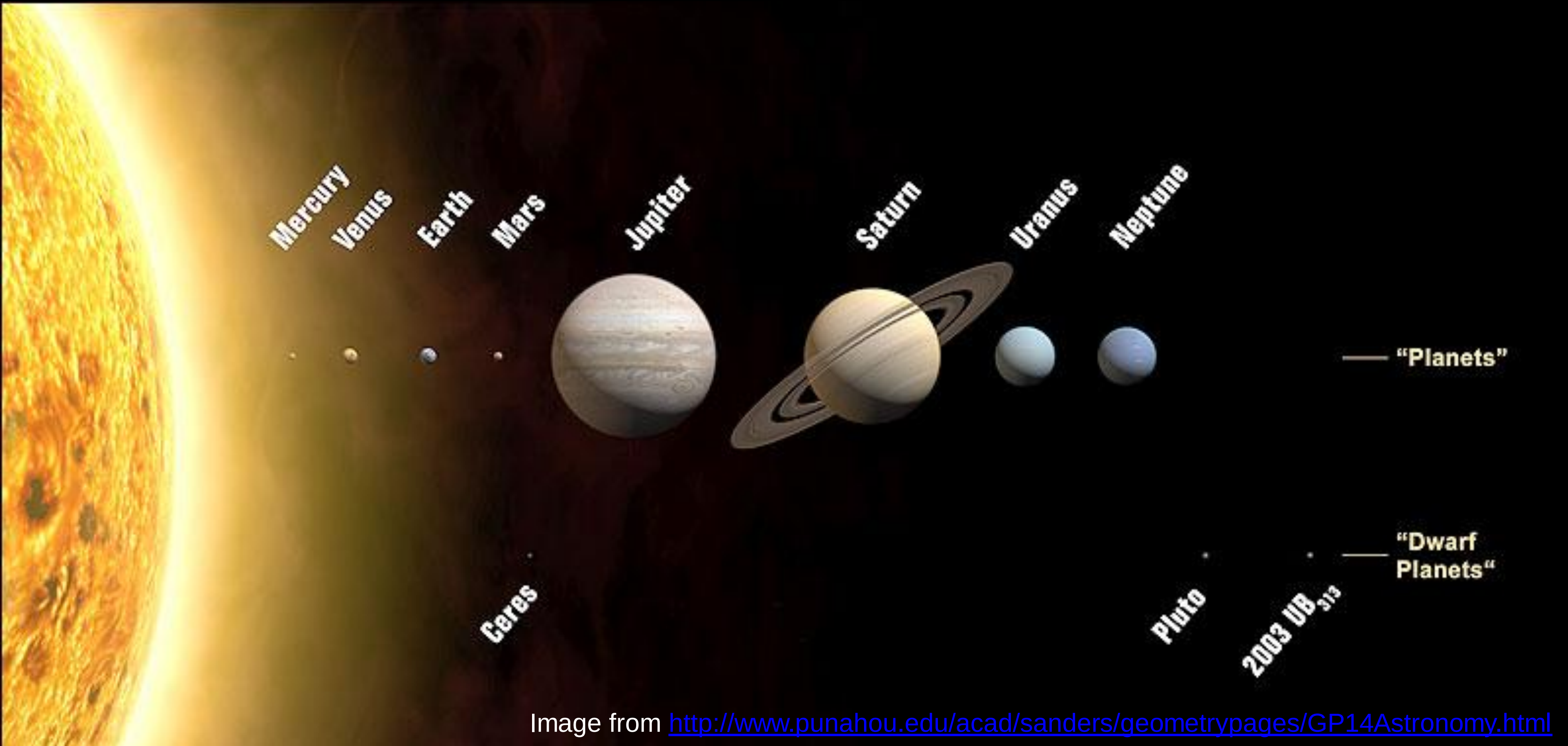


Image from http://www.punahou.edu/acad/sanders/geometrypages/GP14Astronomy.html

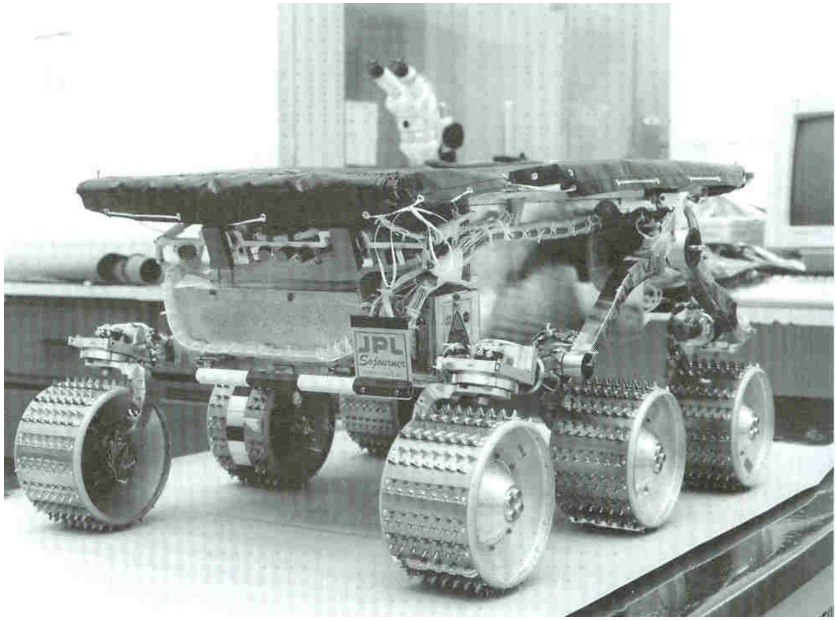
Mars Rovers

1996 Mars Pathfinder “Sojourner” (SEMI-AUTONOMOUS)

- 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)*

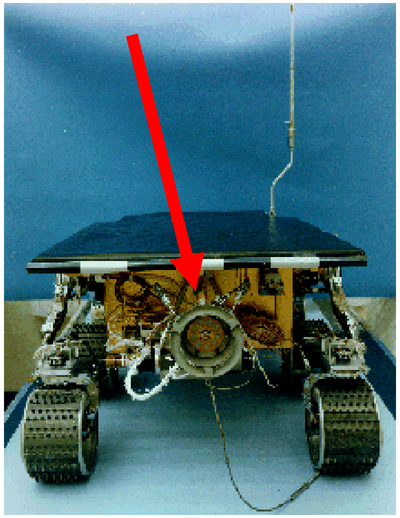
Image from: Young, A.H. ***Lunar and planetary rovers: the wheels of Apollo and the quest for mars***, Springer; 1 edition, August 1, 2006.

Mars Rovers

1996 Mars Pathfinder “Sojourner” (SEMI-AUTONOMOUS)

Sensors for scientific data
(not used in Navigation)

Alpha Proton X-Ray Spectrometer



Atmospheric Structure Instrument/Meteorology Package

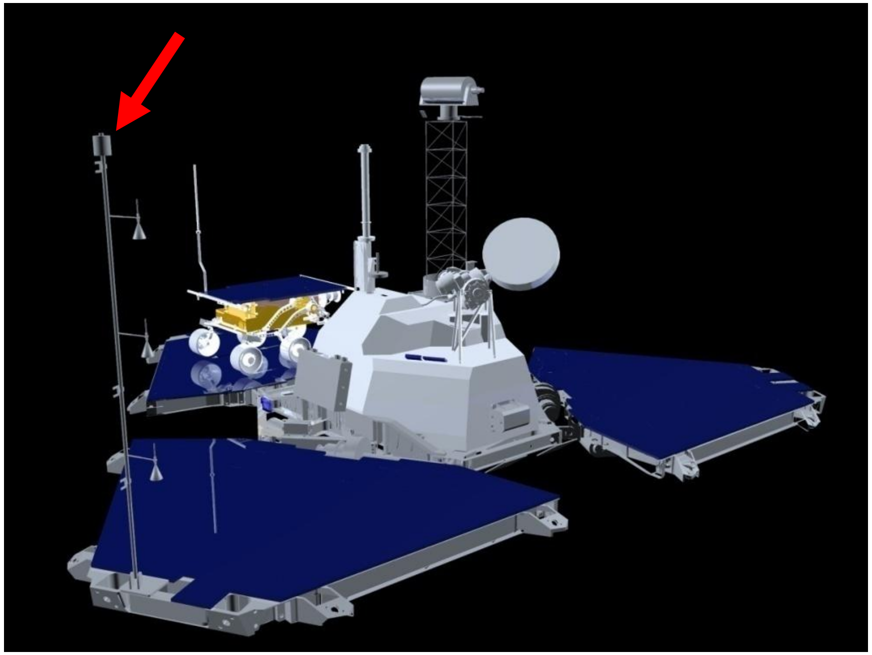


Image from: http://marsprogram.jpl.nasa.gov/MPF/mpf/sci_desc.html
Image from: http://starbase.jpl.nasa.gov/mpfl-m-asimet-3-rdr-surf-v1.0/mpam_0001/document/asmtinst.htm

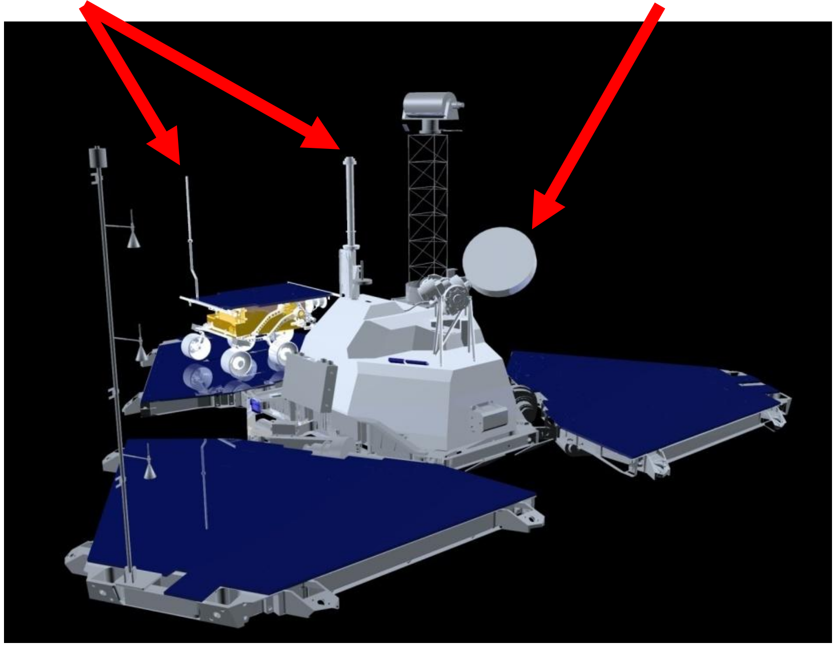
Mars Rovers

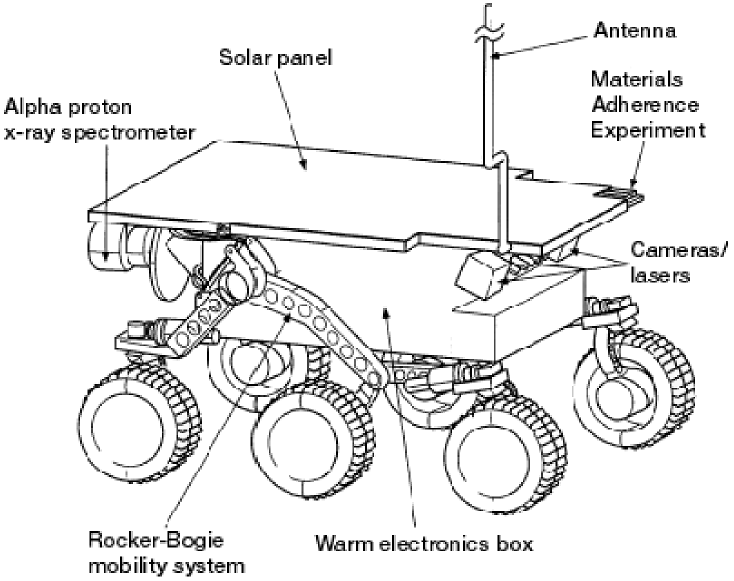
1996 Mars Pathfinder “Sojourner” (SEMI-AUTONOMOUS)

Low-gain antennae for comm between rover and lander

High-gain antenna for comm with Earth

Since tele-operated from earth, **communication is part of navigation**





Cameras and lasers 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

Mars Rovers

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

(SEMI-AUTONOMOUS)

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

AUTONOMY:

- Terrain Navigation with obstacle avoidance
- Pose estimation = *f* (wheel rotation, accelerometer, and angular velocity)
- 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

2010 UPGRADE UPLOADED:

Opportunistic Autonomous **E**xploration for **G**athering **I**ncreased **S**cience system (AEGIS)

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.

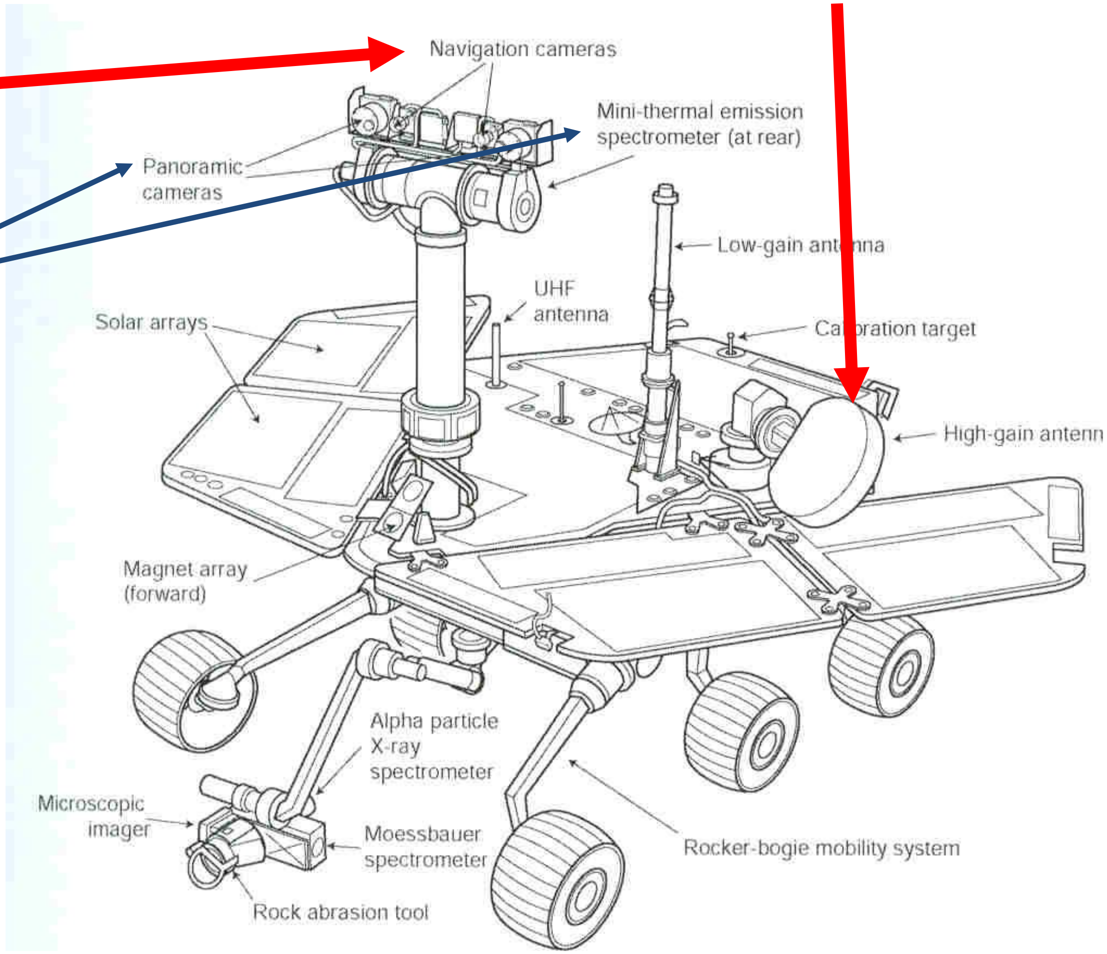
SOURCE: T. Estlin. et. al.(2009). **Automated Targeting for the MER Rovers**. In *Proceedings of the Third IEEE International Conference on Space Mission Challenges for Information Technology, 2009. SMC-IT 2009*. IEEE Press.

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

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

(SEMI-AUTONOMOUS)



Since still often tele-operated, communication is part of navigation

Cameras dedicated to Navigation

Other Imaging sensors

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

<u>2004</u>: NASA Mars Explorer Rovers “***Spirit” and “Opportunity”***

(SEMI-AUTONOMOUS)

Scientific data

Used for **A**utonomous
Exploration for **G**athering
Increased **S**cience system
(AEGIS)

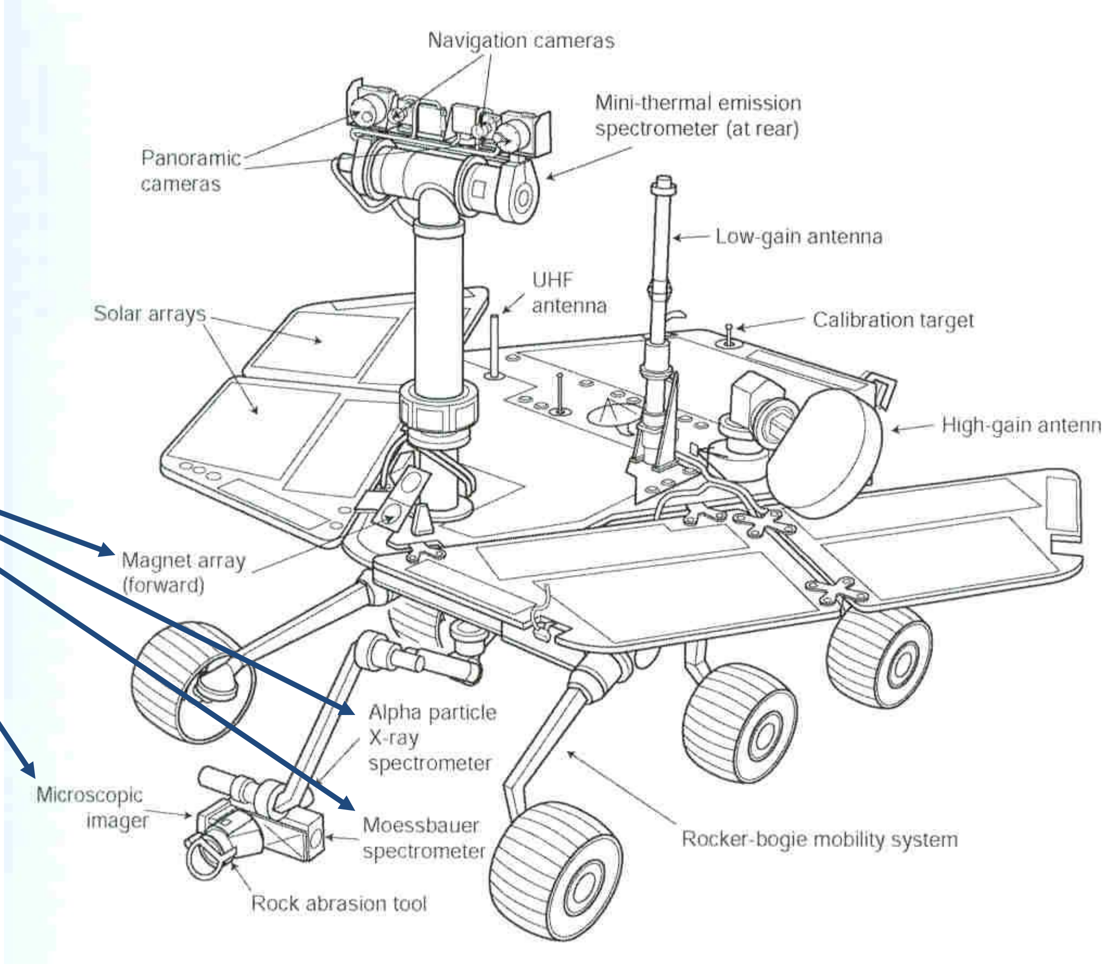


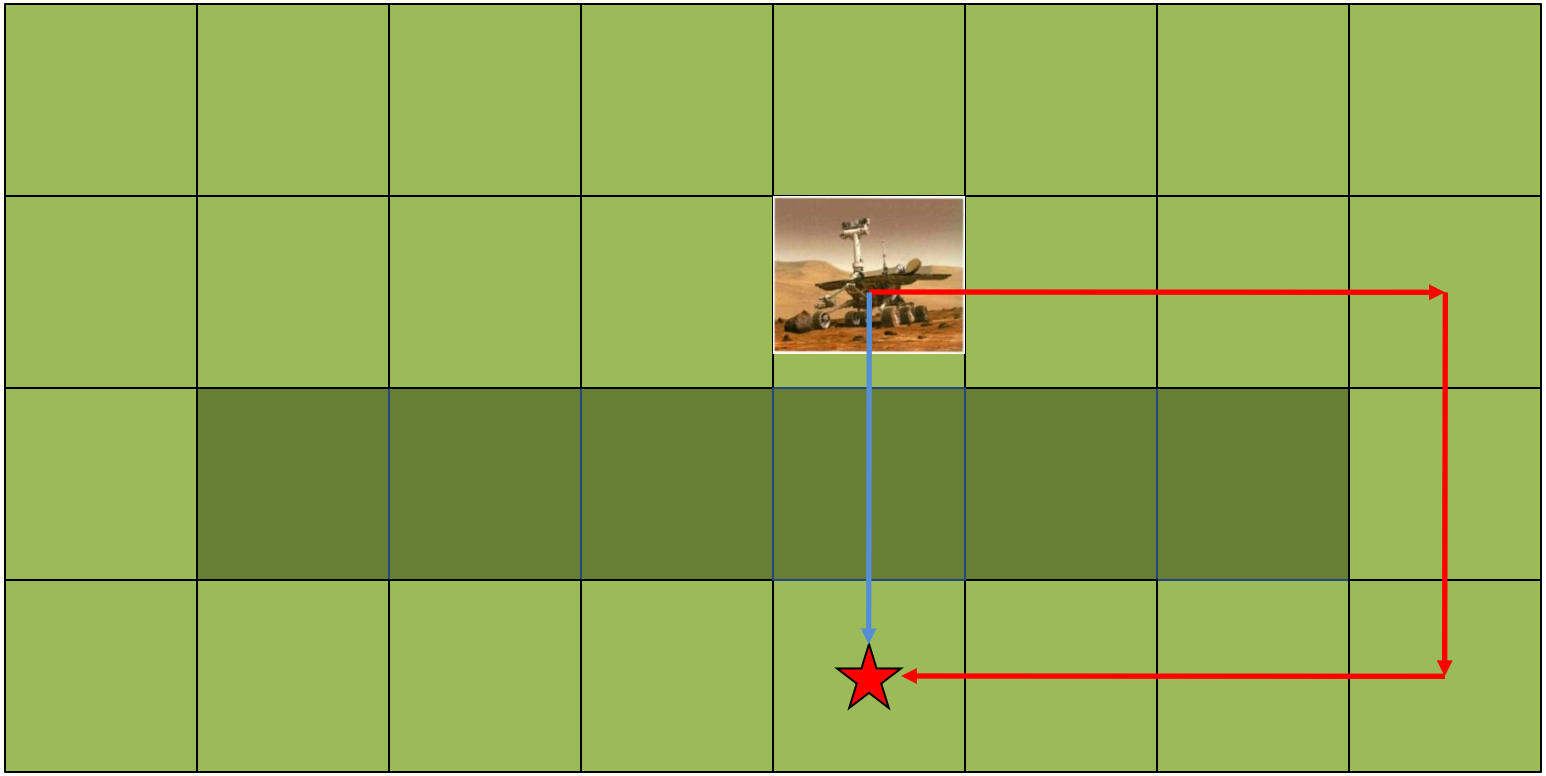
Image from: Young, A.H. ***Lunar and planetary rovers: the wheels of Apollo and the quest for mars***, Springer; 1 edition, August 1, 2006.

Mars Rovers

2004: NASA Mars Explorer Rovers “***Spirit” and “Opportunity”***

(SEMI-AUTONOMOUS)

PROBLEM with Local-Path-Planner (“AutoNav”): Hazard avoidance won't allow rover to drive through unsafe area, but shortest path directives won't allow enough deviation from straight-line path for rover to get around hazard. 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.

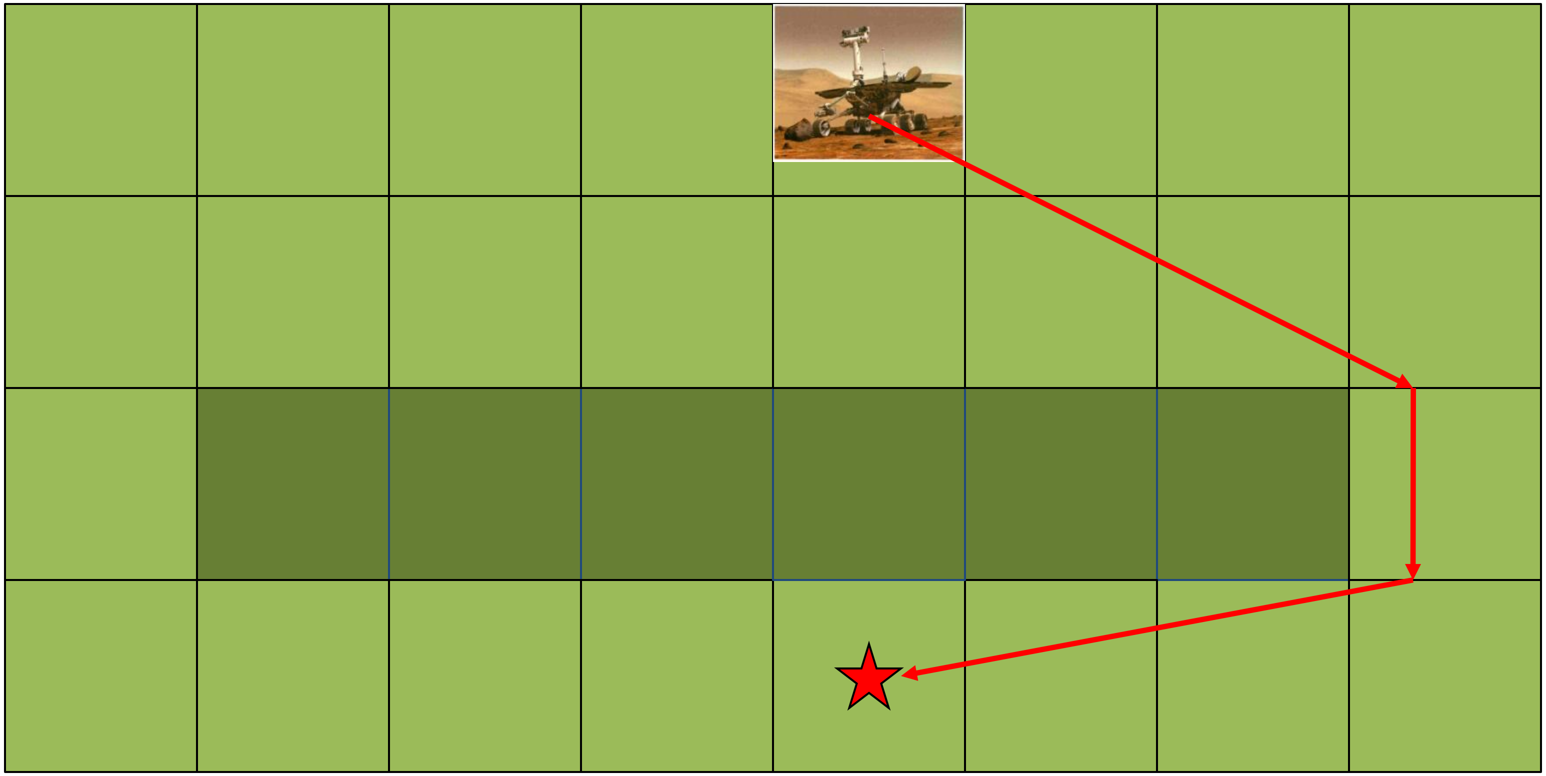
Rover Image from: Young, A.H. ***Lunar and planetary rovers: the wheels of Apollo and the quest for mars***, Springer; 1 edition, August 1, 2006.

Mars Rovers

2004: NASA Mars Explorer Rovers “***Spirit” and “Opportunity”***

(SEMI-AUTONOMOUS)

SOLUTION: 2006 uploaded Global-Planner (“Field D*”) uses forethought yielded by a large map *(plus an “interpolative cost” methodology)* 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.

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

Future Mars Rovers

2011: NASA ***Mars Science Lab*** ***"Curiosity"***

(SEMI-AUTONOMOUS)

Will navigate up to 5km from landing site and find & sample scientific events

AUTONOMY:

- **Global** path planner See: http://mars.jpl.nasa.gov/msl/mission/technology/planetarymobility/
- Terrain prediction (for slip compensation)
- **Autonomous Science** to predict & detect novel science events
- **Motion compensation** while excavating/drilling

(November 2011 Launch)

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://nssdc.gsfc.nasa.gov/planetary/mars_future.html

Future Mars Rovers

2016: European Space Agency (ESA)

"ExoMars" (SEMI-AUTONOMOUS)

Global Path Planner

http://www.esa.int/SPECIALS/ExoMars/SEM2YIAMS7F_0.html

Many contributing countries

- http://www.europlanet-eu.org/demo/index.php?option=com_content&task=view&id=92&Itemid=30

Part of *"AURORA Exploration Program"*

- http://www.esa.int/esaMI/Aurora/SEMLI27X9DE_1.html

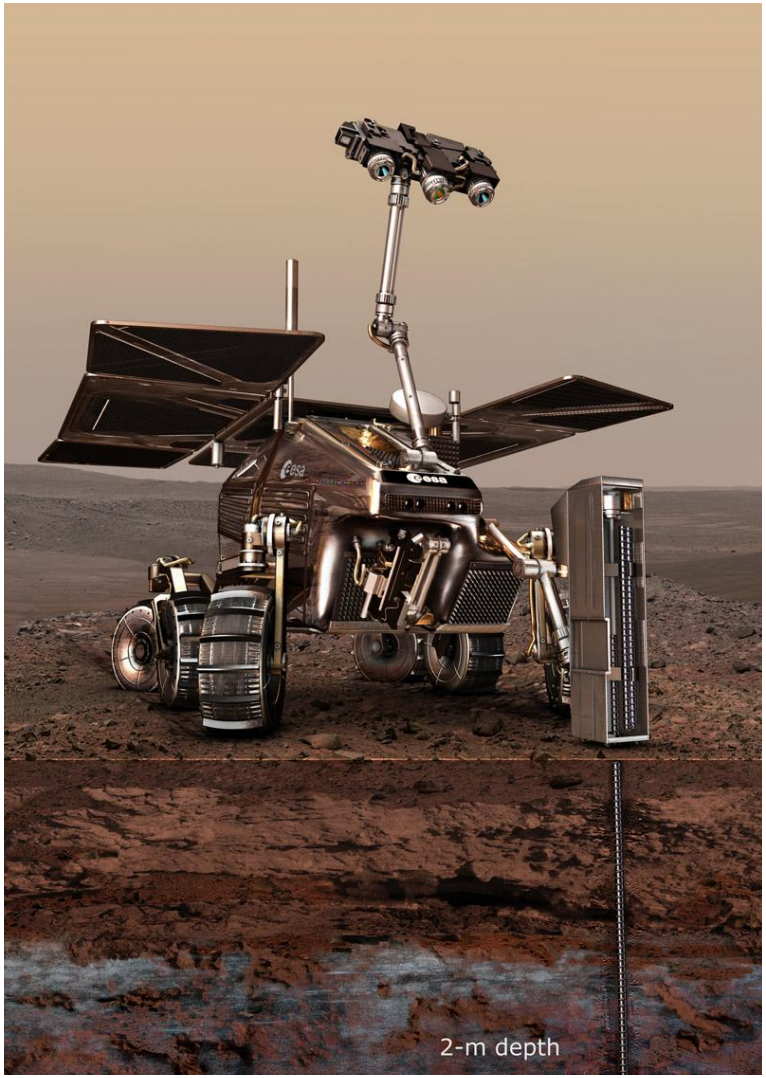
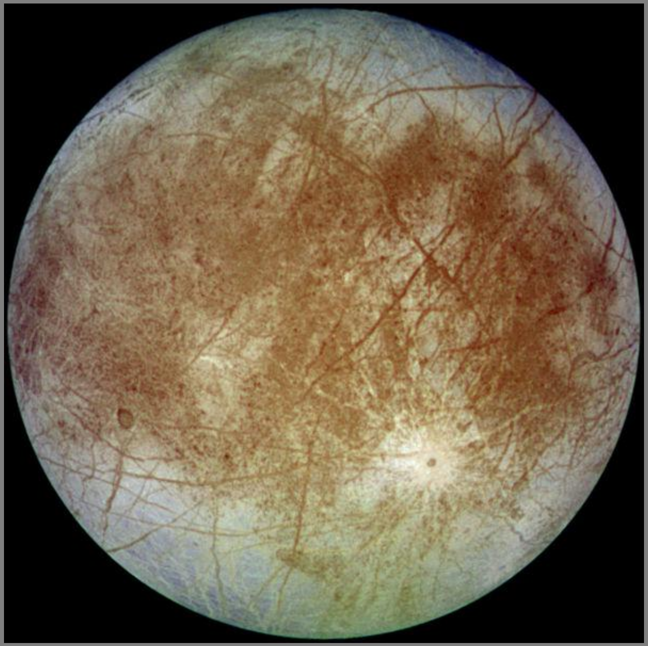


Image from: http://www.nasa.gov/centers/jpl/news/urey-20070209.html

2020 *Europa-Jupiter System Mission (EJSM)*

Two parts:
NASA-led Jupiter Europa Orbiter (JEO)
ESA-led Jupiter Ganymede Orbiter (JGO)

will explore Jupiter System then orbit Europa and Ganymede to characterize water oceans beneath their ice



Europa

Ganymede

Image: http://wgbis.ces.iisc.ernet.in/envis/Remote/section1917.htm

SOURCE: http://opfm.jpl.nasa.gov/europajupitersystemmissionejsm/

Jupiter and it’s moon Europa

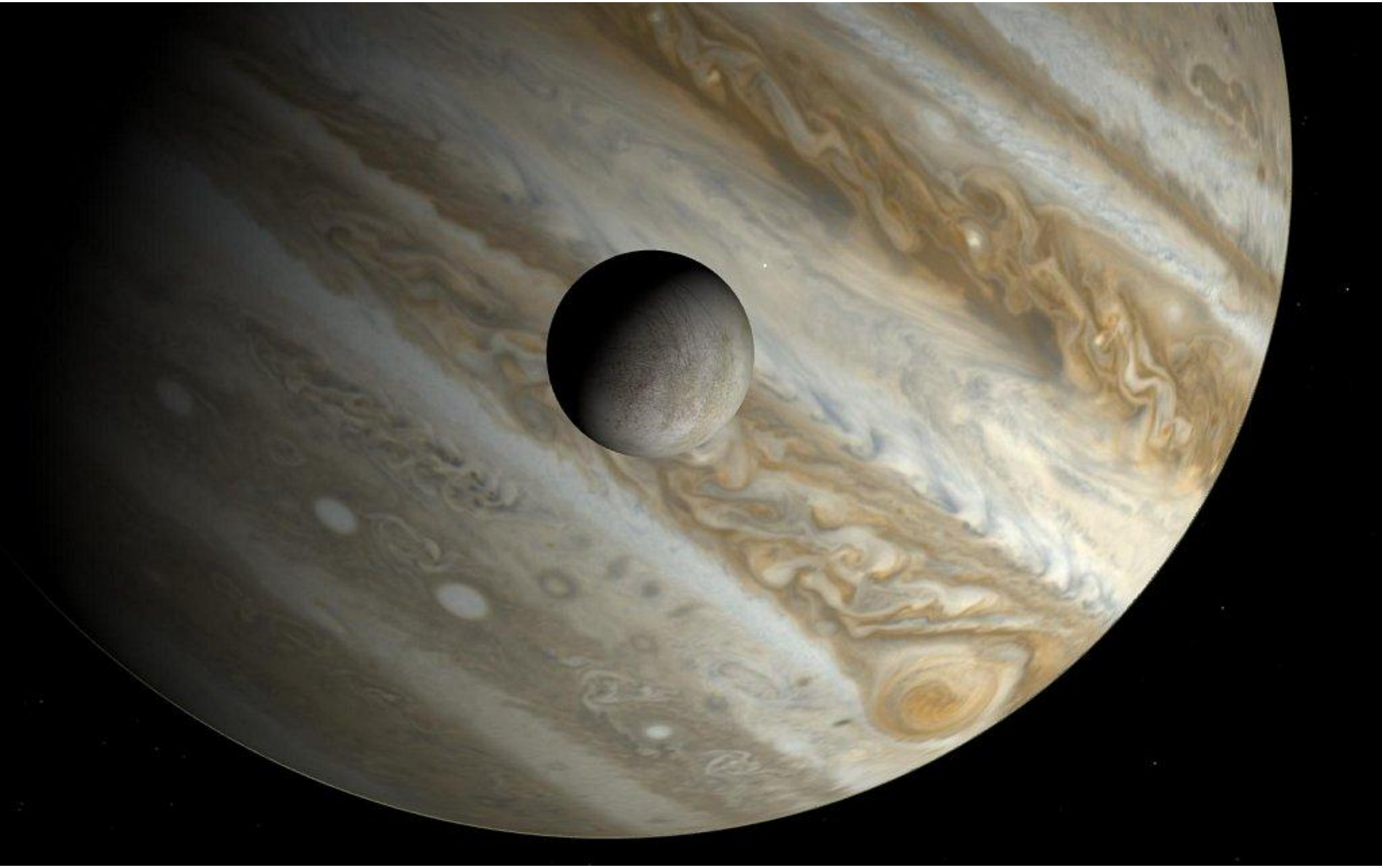


Image from: http://cabfst28.cnea.gov.ar/~abramson/celestia/gallery/slides/Jupiter-Europa.html

Our Moon and Europa compared to Earth

Image from: Image:Mercury_Earth_Comparison.png, Image:Full Moon Luc Viatour.jpg and Image:Europa-moon.jpg by --CWitte

Ganymede and Europa

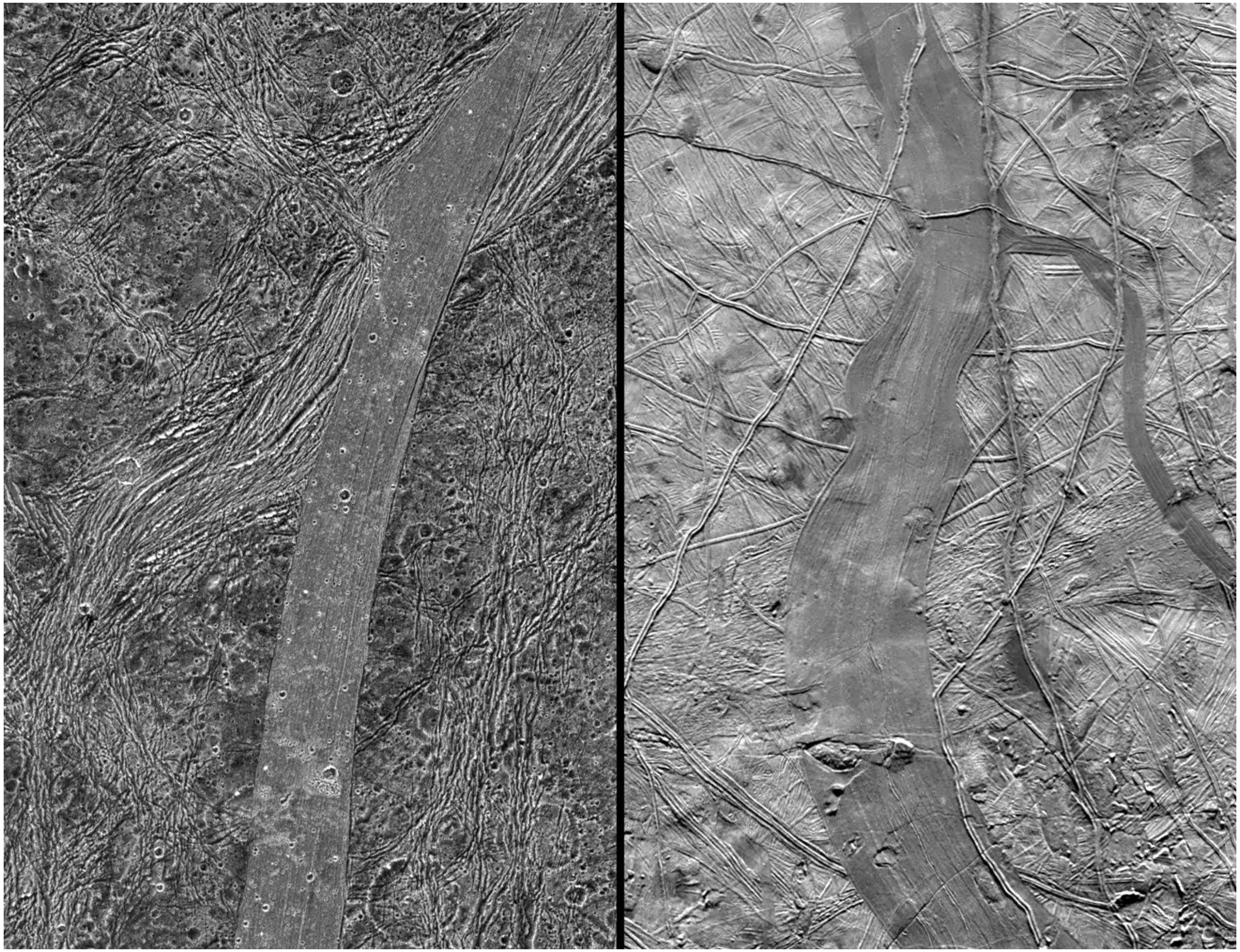
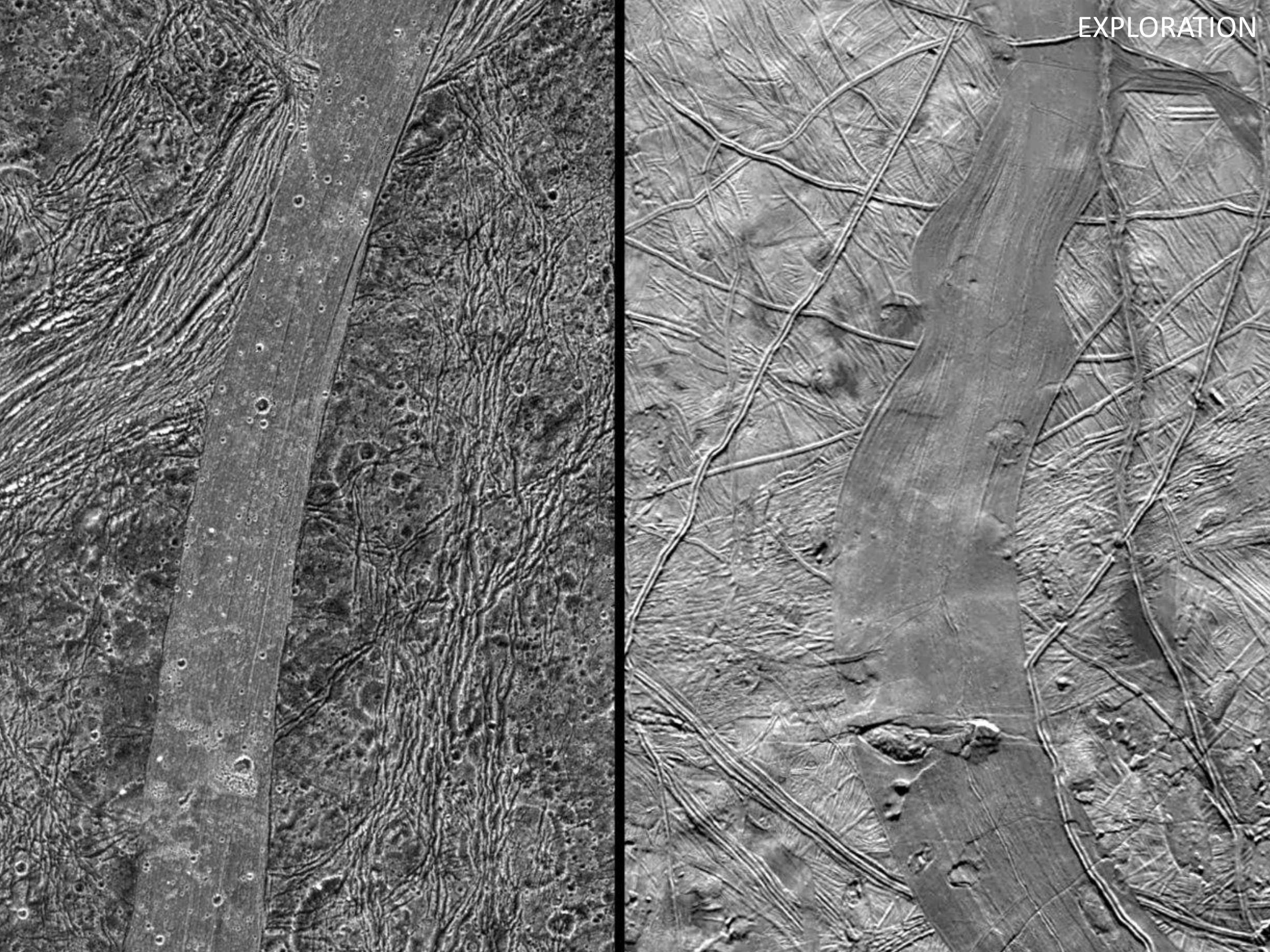
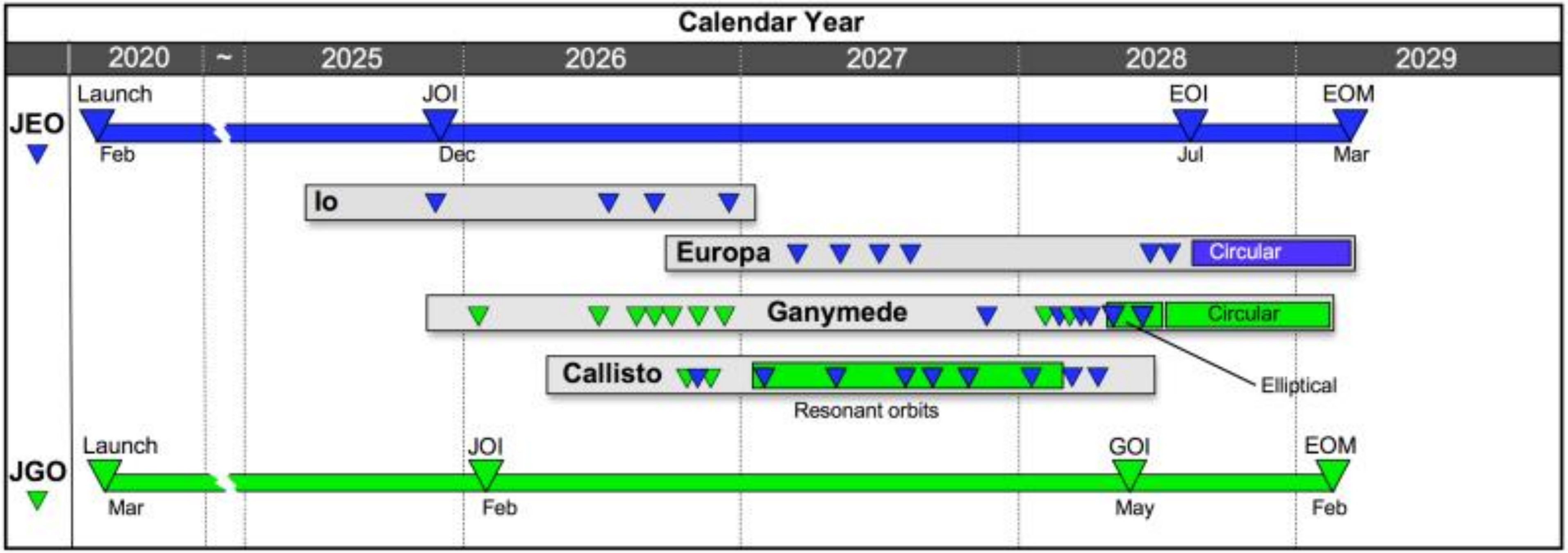


Image from: http://www.nasaimages.org/luna/servlet/detail/NVA2~14~14~24939~124662:Comparison-of-Ganymede-and-Europa-f

EXPLORATION



2020 ESA/NASA
Europa Jupiter System Mission"(EJSM)



SOURCE: http://opfm.jpl.nasa.gov/europajupitersystemmissionejsm/

Could there be life in Europa's ocean ?

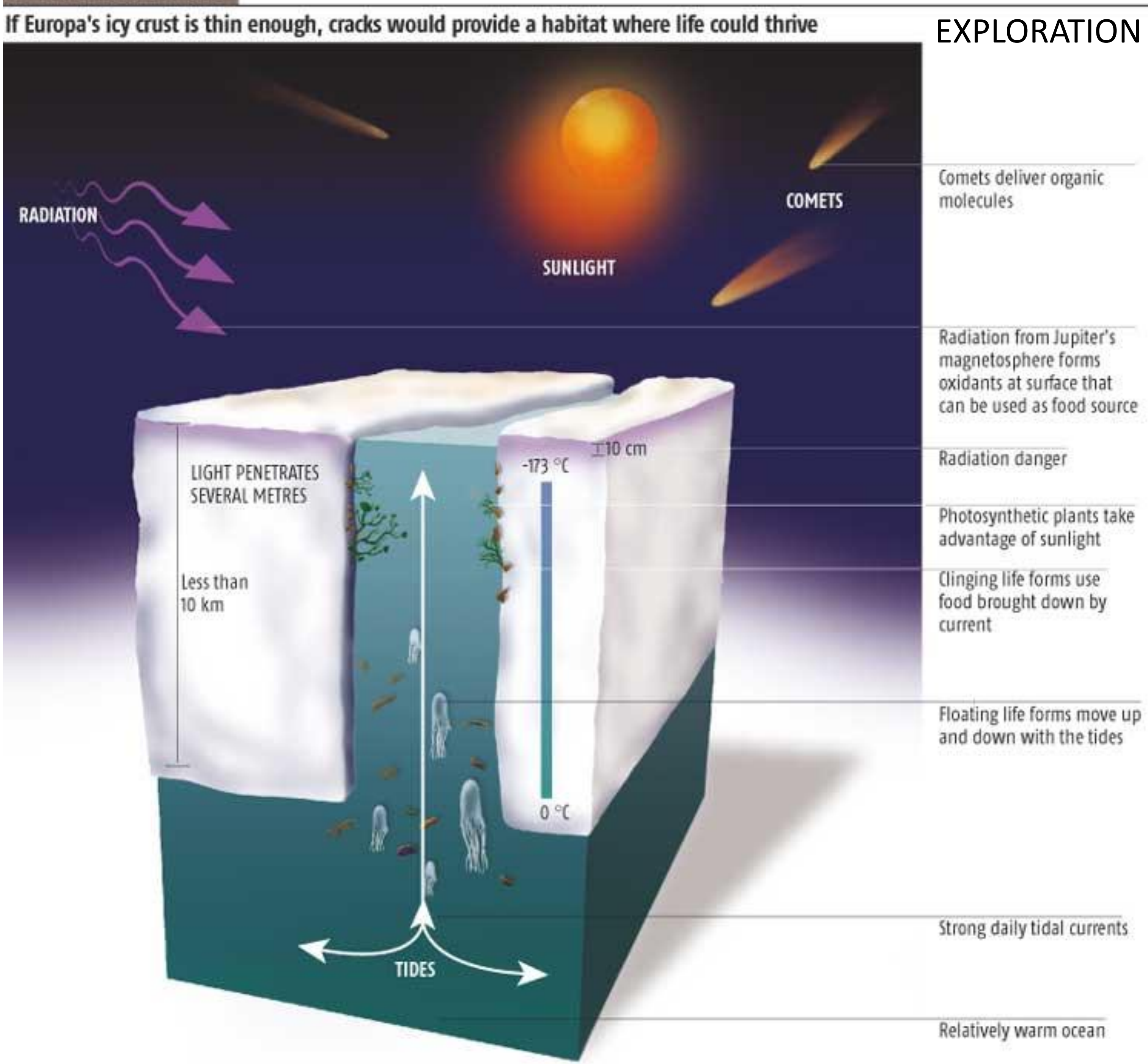


Image from http://www.newscientist.com/article/dn2929-thin-ice-opens-lead-for-life-on-europa.html

Design a Rover for Europa

Optional project for
University of Trento, Italy Ph.D. course
"Advanced Robotics with Applications to Space Exploration"
J. Wunderlich, Visiting Faculty, 2009

Also now be a project for
Elizabethtown College Advanced Undergraduate course
"Artificial Intelligence and Robotics"
J. Wunderlich, Ph.D. Associate Professor of Engineering

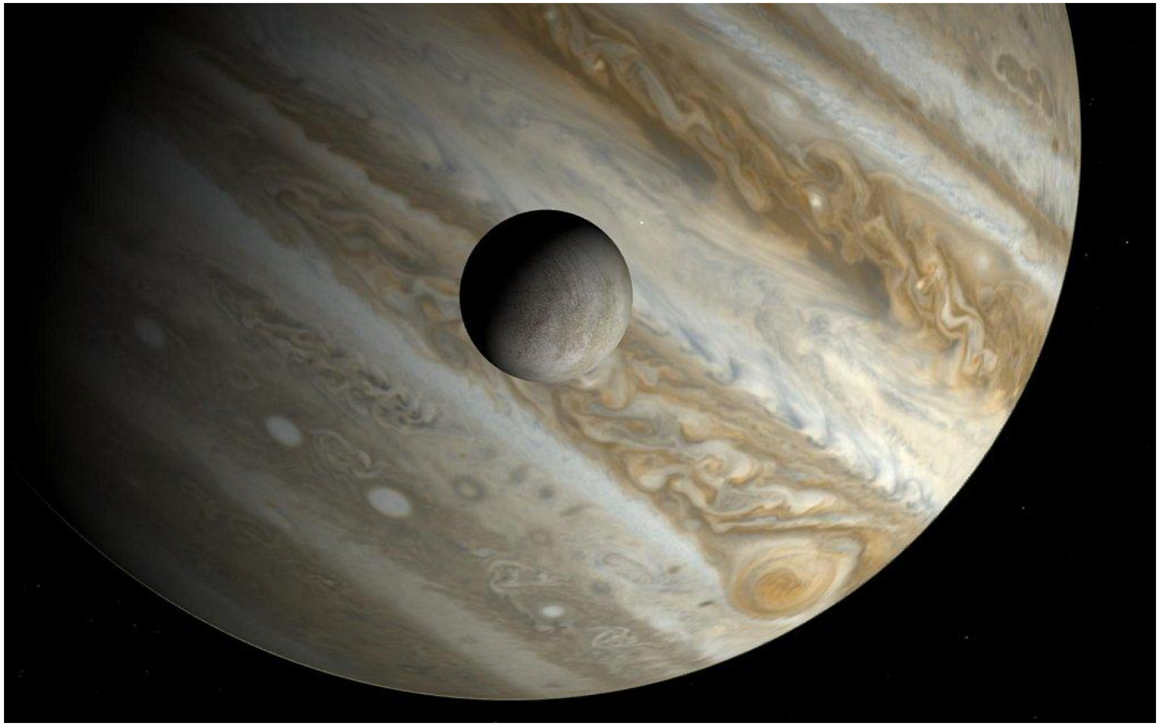


Image from: http://cabfst28.cnea.gov.ar/~abramson/celestia/gallery/slides/Jupiter-Europa.html
Image from: http://www.ing.unitn.it/~devol/
Arial Image: *lost link*

1989: NASA ***Galileo*** image of Europa’s surface

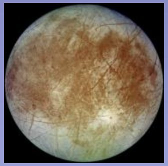
Spots are approximately 10km across

These spots could be from relatively warmer ocean below interacting with icy surface

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

Design a Rover for Europa

EXPLORATION



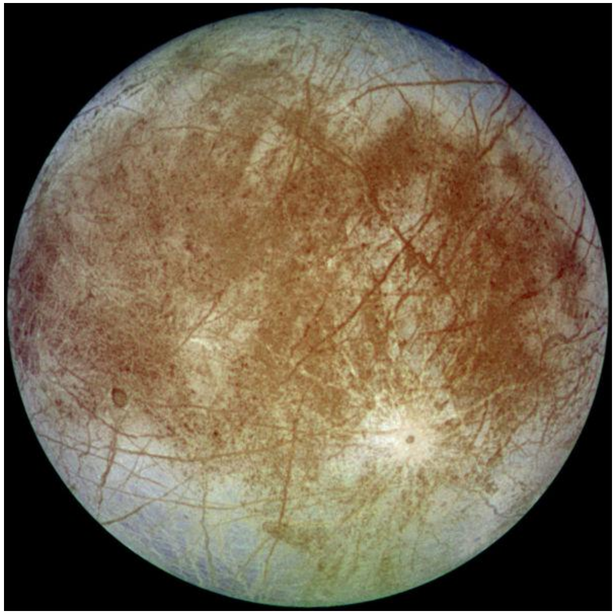
Design a FULLY-AUTONOMOUS rover for the flat icy Surface. Then penetrate 200 meters of ice.

When water reached, either:
(1) Act as Underwater Vehicle, or
(2) Deploy swarm of 10cm-long UUV’s

Maintain communication between robot(s), base-station, orbiters, and earth. Base station creates simulation of robot environment(s)

A PROBLEM TO SOLVE

For unclear goals in cluttered environments, complex sensor fusion can cause a kind of ***"sensory overload"*** inhibiting robot progress

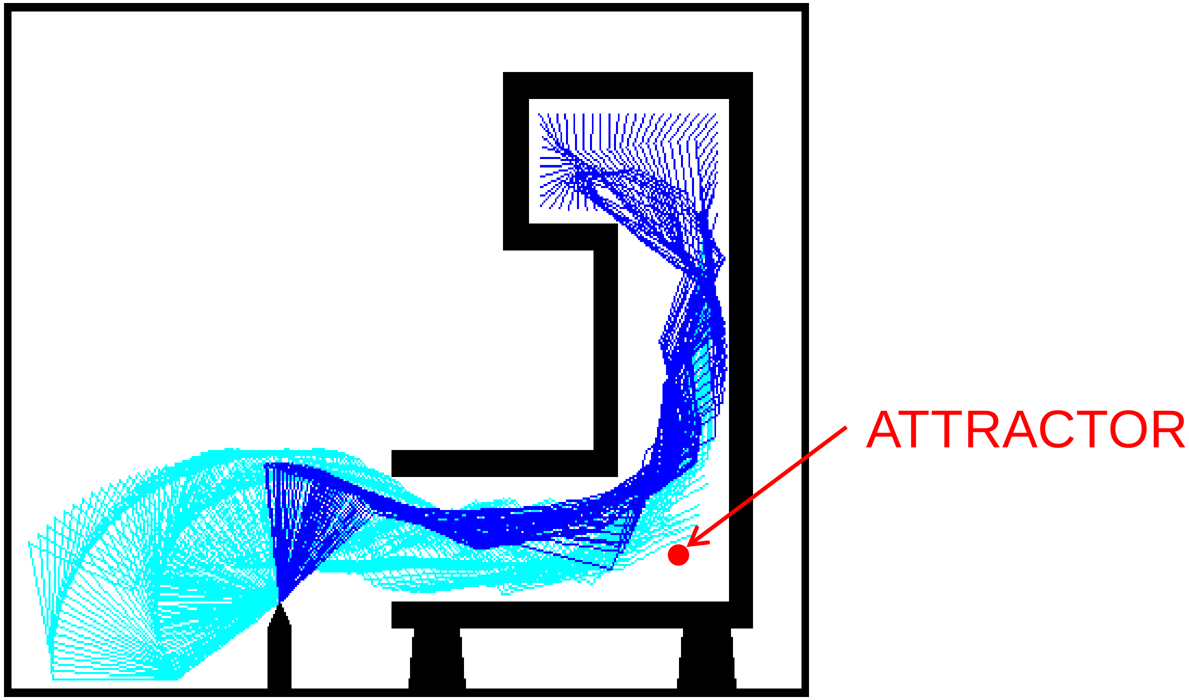


RECOMMENDED SOLUTION

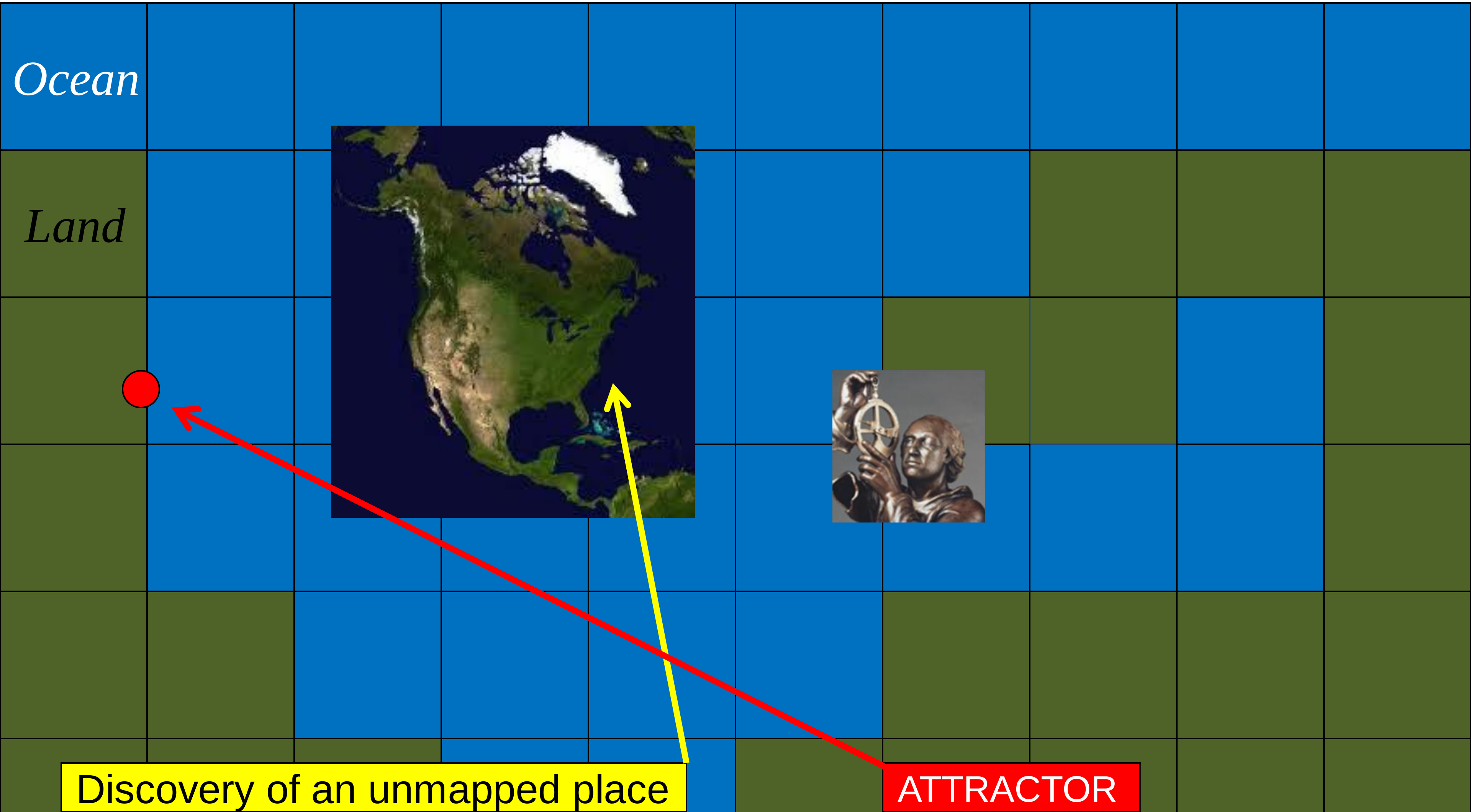
For unclear goals in cluttered environments, CREATE **“ATTRACTORS”**

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.

(“Attractor” Concept originally published in J. Wunderlich 1996 Ph.D. Dissertation)



Christopher Columbus



Ocean

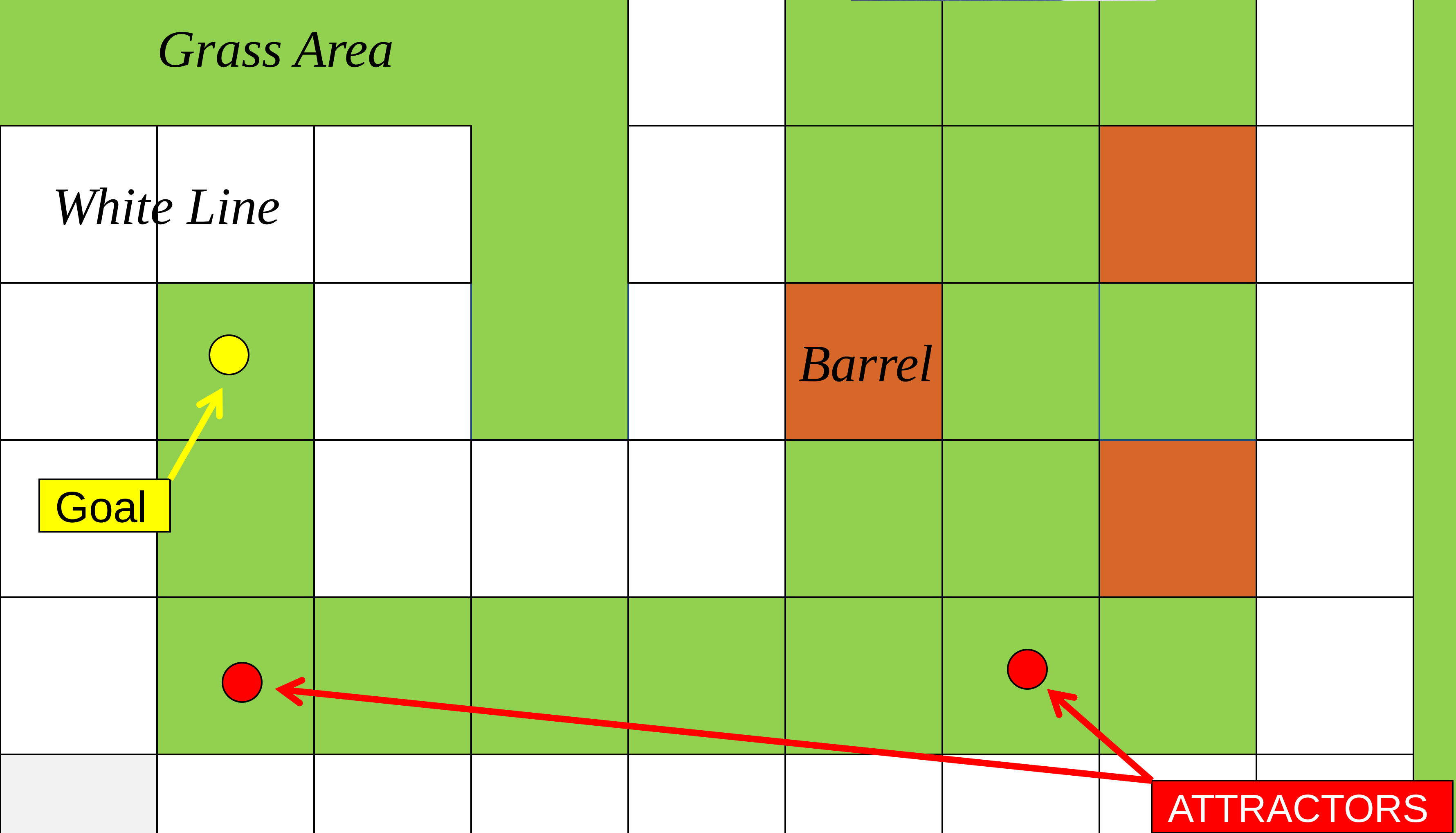
Land

Discovery of an unmapped place

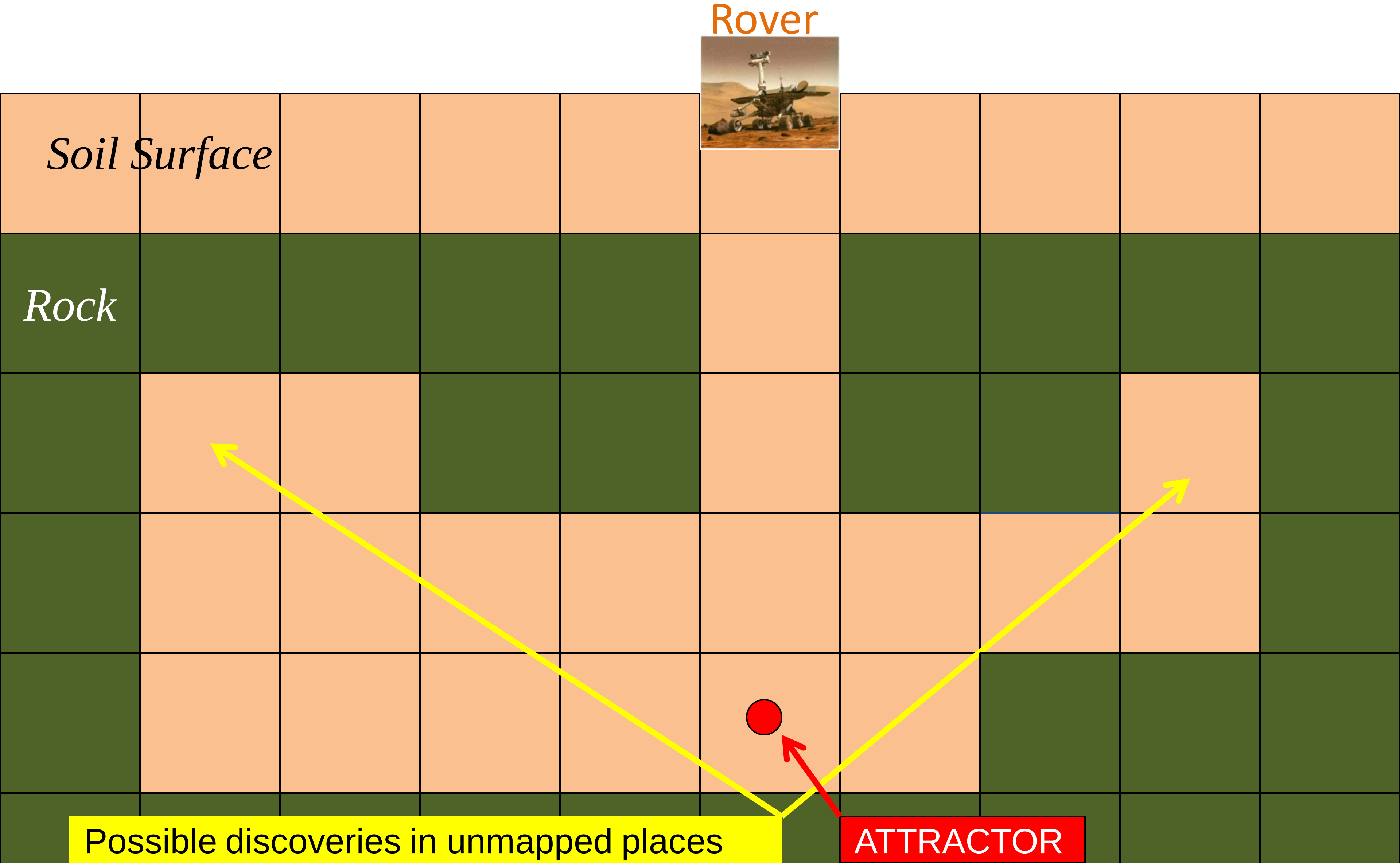
ATTRACTOR

EARTH Obstacle Course

WunderBot



MARS Surface



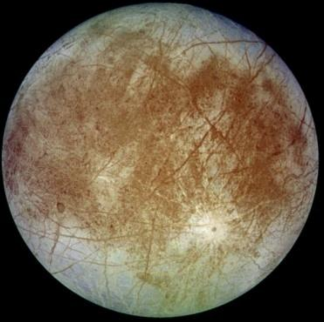
Rover

Soil Surface

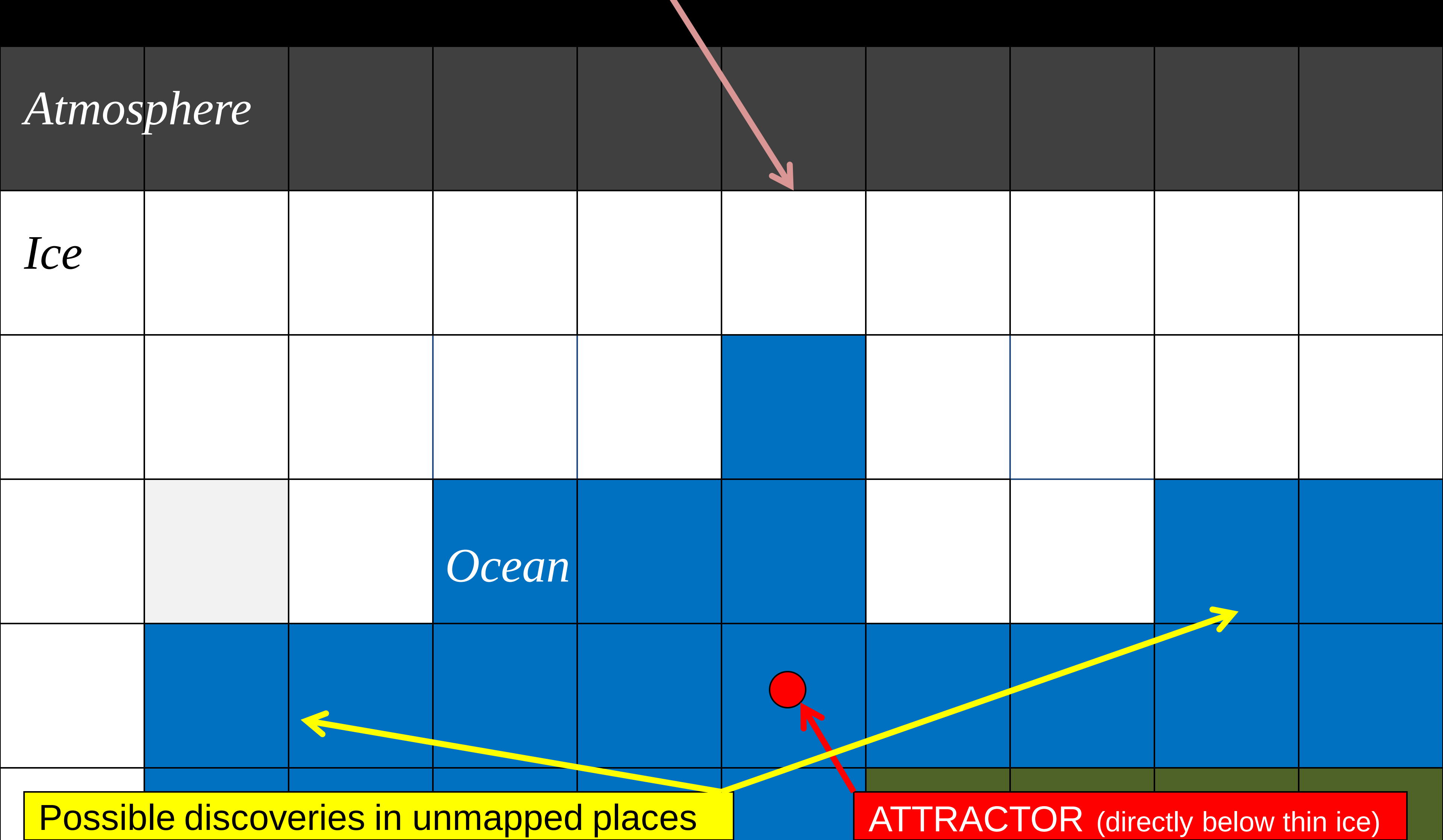
Rock

Possible discoveries in unmapped places

ATTRACTOR



Europa



Future rover could penetrate ice here

Possible discoveries in unmapped places

ATTRACTOR (directly below thin ice)

Mobility Options

LEGS

Justin Vincent

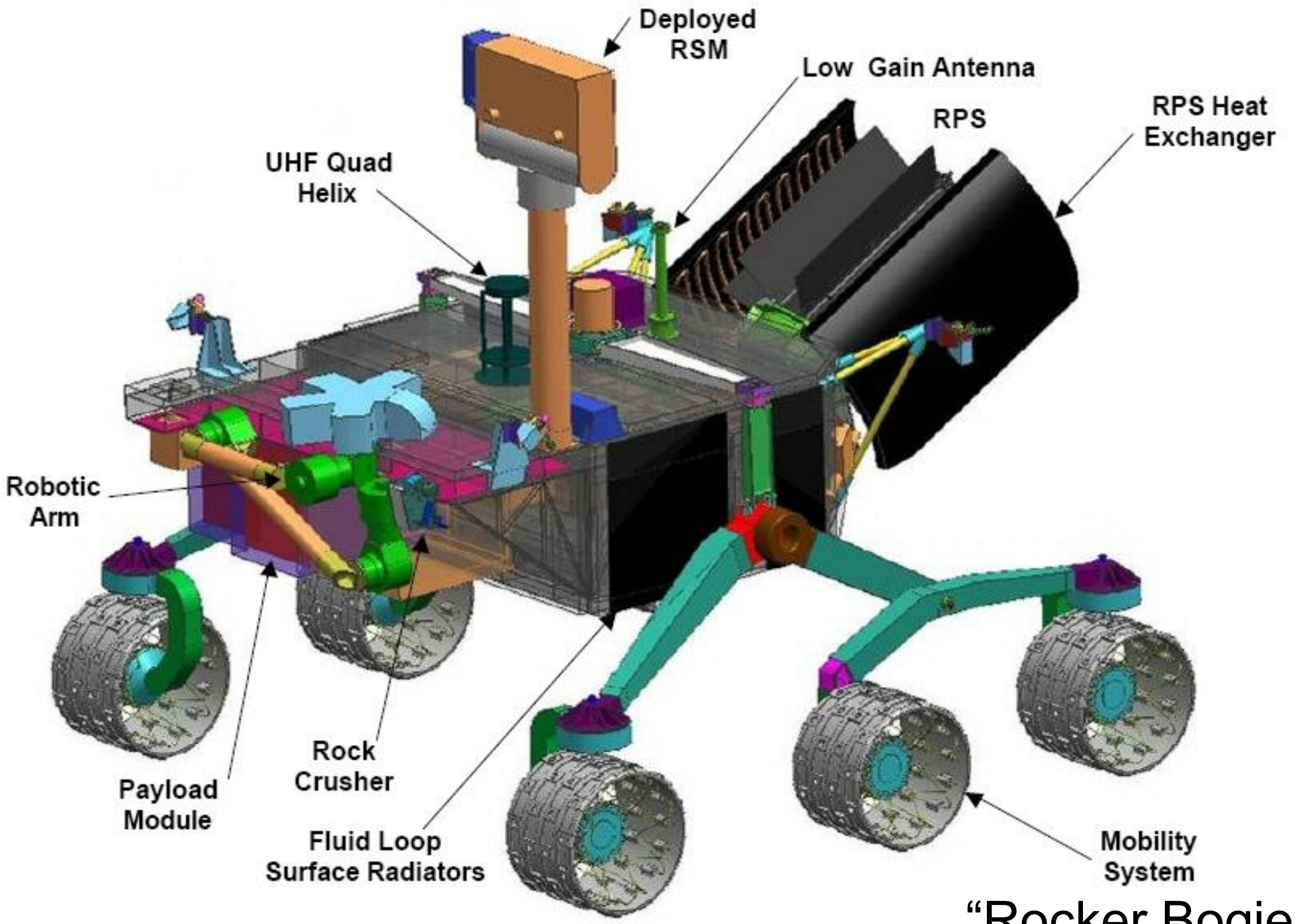
(J. Wunderlich student)

John Deere Co.

VIDEO: http://www.youtube.com/watch?v=0gk-yQ1H3M8

Mobility Options

2011 Mars Science Lab “Curiosity”



“Rocker Bogie”

Image from: http://centauri.larc.nasa.gov/msl/MSL_cfg-dwg_040608.pdf

Mobility Options

For full autonomy, need adaptive mobility on land

Honda's "Asimo"

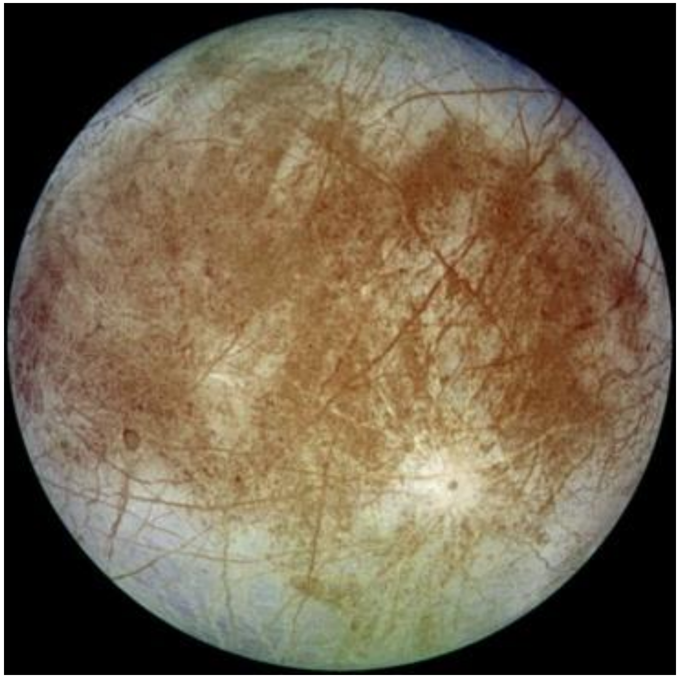
VIDEO : http://www.youtube.com/watch?v=Q3C5sc8b3xM

Boston Dynamics's "Big Dog"

VIDEO: http://www.youtube.com/watch?v=cNZPRsrwumQ

Mobility Options

May need adaptive mobility in oceans

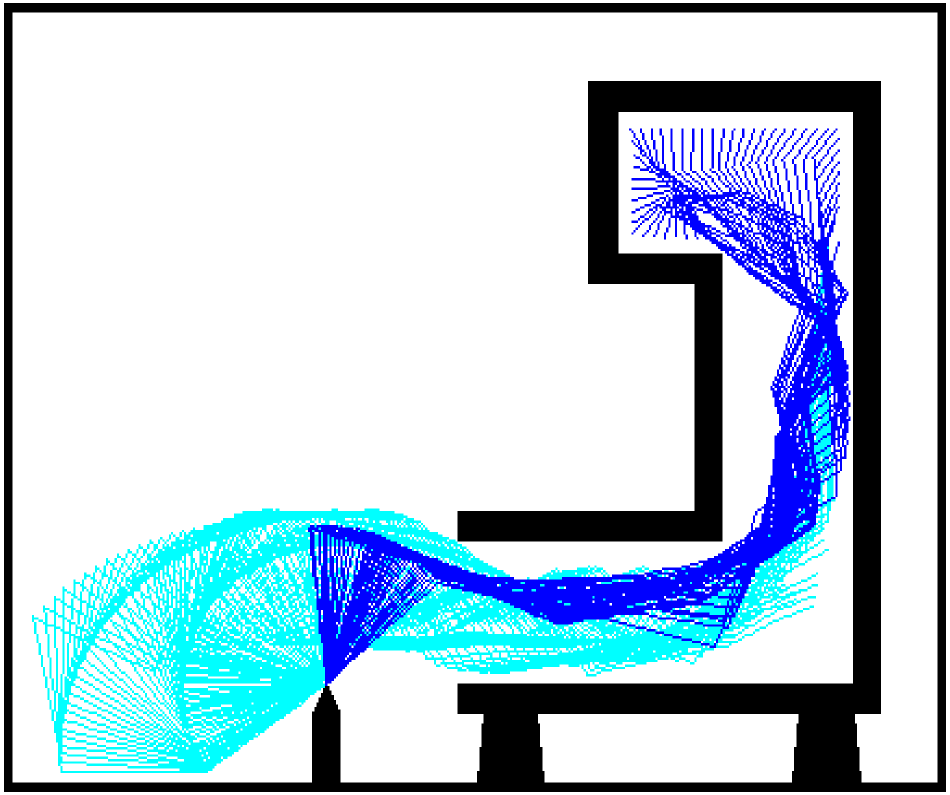


“Aquabot”

Henderson, S., Shreshtha, S., Wunderlich, J.T. (2004). **A high speed AUV test platform** *(submitted to U.S. government conference)*.

Mobility Options

ARMS



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.

Add MANIPULABILITY
to mobile platforms

NASA ***Mars Science Lab "Curiosity"***
(November 2011 Launch)

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

Recall this slide…….

EXPLORATION

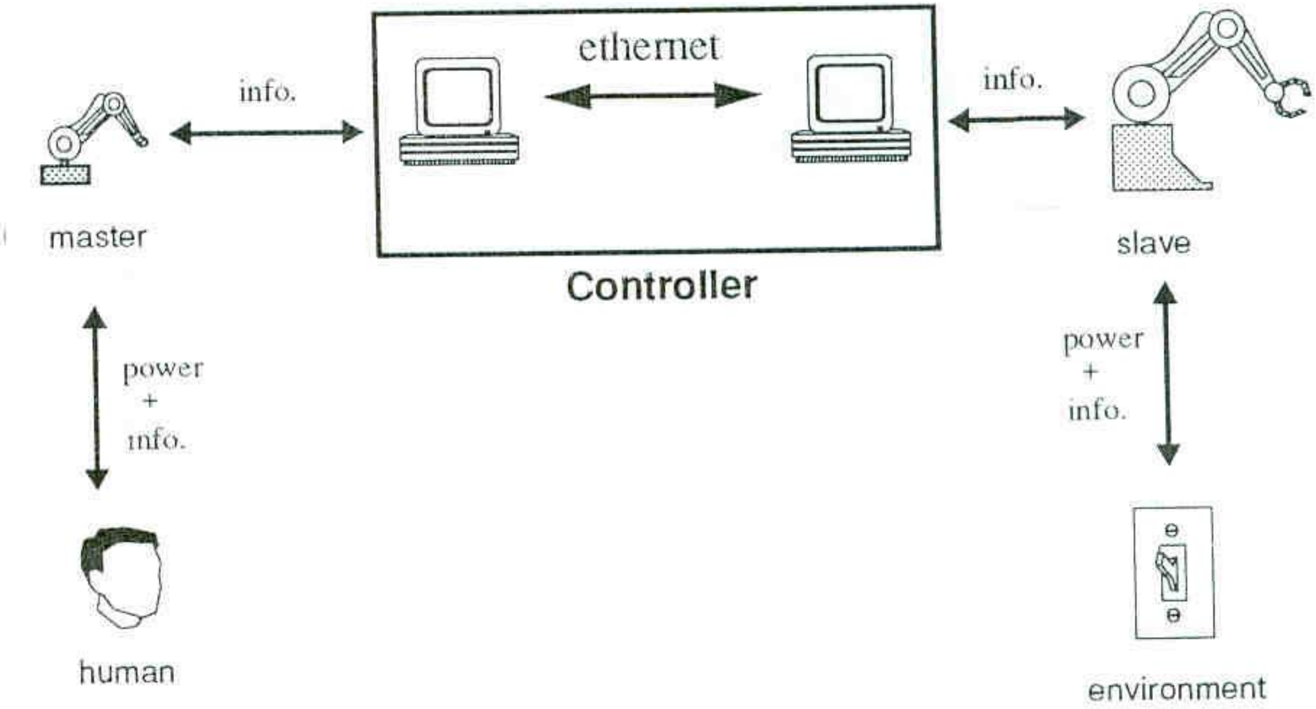
- Robots protect explorers from remote dangers
- OK to leave a robot in a distant place *(retrieving human astronauts is very expensive)*

Autonomy Risks: Very expensive robots destroyed

Mitigation: Ensure high-quality autonomy programming

MANIPULABILITY FOR THE DISABLED

FIGURE 1. Test-Bed Control Scheme.



Head of quadriplegic person moves one Robotic Arm which then results in another more-dexterous Arm performing task

Autonomy Risks: Safety of patient and others

Mitigation: Limit velocity, torque, and motion-range

Wunderlich, J.T., Chen,S., Pino,D. and Rahman,T. (1993). **Software architecture for a kinematically dissimilar master-slave telerobot**. In *Proceedings of SPIE Int'l Conference on Telemanipulator Technology and Space Telerobotics*, Boston, MA: Vol. (2057). (pp. 187-198). SPIE Press.

ASSISTANTS/COMPANIONS

- Always available

Honda's "Asimo"

Autonomy Risks: Frightening; Could hurt people

Mitigation: Limit velocity, torque, and motion-range; Submissive appearance & actions

Image from: http://www.21stcentury.co.uk/robotics/honda_asimo_robot.asp

Computer Advice for Autonomy

Simulation	Real-Time control
Create high-quality model of environment (i.e., not just a cartoon)	Closed loop control of models of physical sub-systems
Complex hardware & software for graphics, model complexity, and minimal programming	**Simplified hardware & code** for fast, compact, fault-tolerant, real-time responses
Feed GLOBAL PLANS to real-time code so it improves it's LOCAL PLANS	Feed LOCAL data to simulation so it can build GLOBAL PLANS

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.*

Mars Rovers' Embedded Computing

1996 ***"Sojourner"***

100 **k**Hz Intel 80C85 CPU
512 Kbytes of RAM
176 Kbytes of flash memory

2004 ***"Spirit"*** *and* ***"Opportunity"***

20-MHz IBM RAD6000 CPU
128 Mbytes of RAM
256 Mbytes of flash memory

2011 ***"Curiosity"***

200-MHz IBM RAD750 PowerPC
256 Mbytes of RAM
2 Gbytes of flash memory

Spirit, Opportunity, *and* ***Curiosity*** use **VxWorks REAL-TIME Operating System** to run many parallel tasks

SOURCES:

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. (available at http://marstech.jpl.nasa.gov/publications/z02_0102.pdf)*

VxWorks tutorial: http://www.cross-comp.com/instr/pages/embedded/VxWorksTutorial.aspx

Advanced Autonomous Robots need Machine Intelligence

But
what
is
"Intelligence"

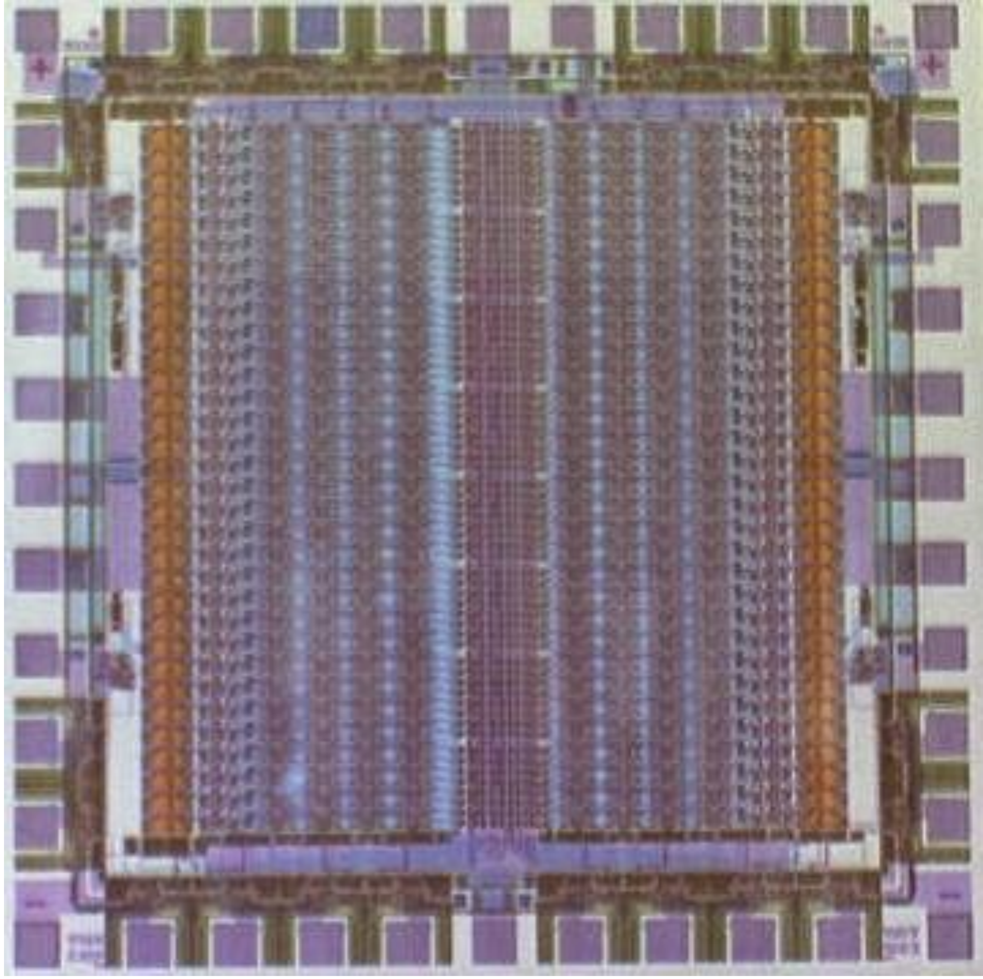
Wunderlich, J.T. (2003). **Defining the limits of machine intelligence.** In *Proceedings of IEEE SoutheastCon, Ocho Rios, Jamaica,* [CD-ROM]. IEEE Press.

		Can human do?	Can bug do? (spider)	Can Conventional Computer Program do?	Can Symbolic AI Program do?	Can Artificial Neural Network do?	Comments
	BASIC ANIMAL ABILITIES:						
1	Acquire and retain knowledge	yes	yes	yes	yes	yes	
2	Solve problems	yes	yes	yes	yes	yes	
3	**Learn and adapt**	yes	yes	no	somewhat	yes	**Evolution**
4	Motor coordination	yes	yes	somewhat	somewhat	somewhat	Survival
5	Acquire energy	yes	yes	somewhat	somewhat	somewhat	Survival
6	Protect self	yes	yes	somewhat	somewhat	somewhat	Survival
7	Sensory processing	yes	yes	yes	yes	yes	
8	Real-time thought	yes	yes	yes	yes	yes	
9	React instinctively	yes	yes	no	not yet	not yet	
10	Anticipate	yes	yes	yes	yes	yes	
11	Predict	yes	yes	yes	yes	yes	
12	Communicate	yes	yes	yes	yes	yes	
13	Generalize	yes	yes	no	somewhat	yes	
14	Associate	yes	yes	somewhat	somewhat	yes	
15	Recognition patterns	yes	yes	somewhat	somewhat	yes	
16	Robust under partial failure	yes	yes	no	no	yes	
17	Autonomous thought	yes	yes	no	somewhat	somewhat	
18	Drive to reproduce	yes	yes	no	not yet	not yet	
19	Stability, repeatability, predictability	somewhat	somewhat	yes	yes	somewhat	Uncertainty
20	Multitask	yes	yes	yes	no	yes	

		Can human do?	Can bug do? (spider)	Can Conventional Computer Program do?	Can Symbolic AI Program do?	Can Artificial Neural Network do?	Comments
	COMPLEX ABILITIES:						
21	Abstraction	yes	unlikely	no	no	somewhat	
22	Intuition	yes	unlikely	no	not yet	not yet	
23	Common sense	yes	yes	no	not yet	not yet	
24	**Manipulate tools**	yes	no	yes	**yes**	**yes**	**Evolution**
25	Heuristics	yes	yes	somewhat	yes	no	
26	Inference	yes	yes	somewhat	yes	somewhat	
27	Hypothesis testing	yes	somewhat	somewhat	yes	no	
28	Self-discipline, impulse-control	yes	unlikely	no	somewhat	no	
29	Ethical behavior	yes	unlikely	no	somewhat	somewhat	If coded/trained
30	Selective awareness (filtering)	yes	yes	yes	yes	yes	
31	Open to inspection	somewhat	somewhat	yes	yes	somewhat	
32	Emotions	yes	unlikely	no	not yet	not yet	
33	Imagination	yes	unlikely	no	not yet	not yet	
34	Creativity	yes	unlikely	no	not yet	not yet	
35	Passion	yes	unlikely	no	not yet	not yet	
36	Playfulness	yes	unlikely	no	not yet	not yet	Evolution
37	Empathy	yes	unlikely	no	not yet	not yet	
38	Courage	yes	unlikely	no	not yet	not yet	
39	Leadership	yes	unlikely	no	not yet	not yet	
40	Self awareness	yes	unlikely	no	not yet	not yet	
41	Awareness of mortality	yes	unlikely	immortal?	immortal?	immortal?	Replaceable parts
42	Group psychology	yes	unlikely	somewhat	somewhat	somewhat	Networking

Machine Intelligence

- Symbolic AI programs
  - Heuristics, inference, hypothesis-testing, knowledge representation
  - Expert Systems
  - Predicate Calculus, PROLOG, LISP
- Artificial Neural Networks
  - Connectionist architectures *similar* to biological brains
  - Learns by changing inter-neuron connection strengths



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Designing robot autonomy: how tightly should we hold the leash?

Joseph T. Wunderlich, Ph.D.

CONCLUSIONS

- Autonomy needs to be carefully designed to protect life, property, and robots
- Excessive constraints can prevent discovery, or even halt all progress