A Martian Vision:

Impact of JPL Robotics Vision and Mobility Research on the Mars Rovers

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Mars Rovers Explore Slopes

NASA/JPL-Caltech/Cornell

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And Craters
And Mountains

NASA/JPL - Caltech/Cornell
And Discover Buried Treasure
And Overcome Obstacles
And Explore Novel Terrains
Sojourner drove 0.1 km in 0.3 years
Spirit Drove 7.7 km in 6 years

http://marsrovers.nasa.gov/mission/tm-spirit-all.html
Opportunity Drove 43 km in 12.3 years

[Image of Mars surface with craters labeled and a yellow line indicating a path from Eagle Crater to Endeavour Crater.]

Curiosity Drove 13 km in 3.7 years

## Flight Rover Specs

<table>
<thead>
<tr>
<th></th>
<th>Sojourner</th>
<th>MER</th>
<th>MSL</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CPU</strong></td>
<td>80C85</td>
<td>BAE RAD6000</td>
<td>BAE RAD750</td>
</tr>
<tr>
<td><strong>MHz</strong></td>
<td>2</td>
<td>20</td>
<td>133</td>
</tr>
<tr>
<td><strong>RAM (Mbytes)</strong></td>
<td>0.56</td>
<td>128</td>
<td>512</td>
</tr>
<tr>
<td><strong>Non-volatile storage (Mbytes)</strong></td>
<td>0.17</td>
<td>256 flash</td>
<td>4,096 flash</td>
</tr>
<tr>
<td><strong>Stereo Pixels processed per step</strong></td>
<td>20</td>
<td>10,000 - 50,000</td>
<td>40,000 - 200,000</td>
</tr>
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</table>
How Did We Get Here?
Research Rovers Go Way Back

SLRV (1964) (JPL and GM)

Blue Rover (1986)

Robby (1990)

Rocky 4 (1992)

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Courtesy Issa Nesnas
Early Rocker/Bogie Prototype
Blue Rover

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Courtesy Brian Wilcox
Robby
HMMWV
Rocky 4

Courtesy Brian Wilcox
Rovers in 2001

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Sojourner / Marie Curie

Developed by JPL (1994 - 1997) for Mars mission

After successfully arriving at Mars on 4 July 1997, Sojourner acquired images and analyzed rocks for nearly three months.

A cousin of Rocky 7, Sojourner derives its design from the Rocky 4 prototype.

Driven for a total distance of around 100 meters during its lifetime on Mars.
Rocky 7

Developed by JPL (1996-2001+) for long (> 10m) traverses
Rocker-bogey suspension
Includes two manipulators: extendible mast, sampling arm

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FIDO

Developed by JPL (1998 – 2001+) for field training of scientists, preparing for (postponed) Mars Sample/Return mission Concept

Rocker-bogey suspension

Includes extendible mast, coring drill

Automated return-to-lander capability

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Athena Software Development Model

Developed by JPL (1998 - 2000) as prototype for Mars Sample Return rover Concept

Uses FIDO chassis, but with spaceflight-equivalent electronics

Superceded by new requirements for 2003 Mars Exploration Rover

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Nanorover

Developed by JPL (1995 – 2001+) as research rover, then part of MUSES-C mission

4 wheels can move about central axis, enabling rover to self-right

Planned launch in 2002

Includes spectrometer and camera for science instruments

MUSES-CN rover being designed for microgravity environment
JPL Stereo Vision

Robotics Development: Rover Stereo Vision

Rover Stereo Vision

NASA - Planetary

JPL – DDF
Algorithm breakthrough was achieved on 3-D perception with real-time stereo vision

US Army - TARDEC
Simultaneous, synergistic programs to develop navigation and control architectures for unmanned ground vehicles. The architectures were called “Computer-Aided Remote Driving (CARD) and Semi-Autonomous Navigation (SAN)

1987-1989

1990

1991-92

1992-96

1997

1997-2001

2003

Robotics Tech Test Vehicle (RTTV)
Extended real-time stereo-vision for use in CARD for safe-guarded remote driving of HMMWV

DARPA DEMO II
Further extension of stereo-vision for semi-autonomous, off-road navigation of robotic HMMWVs in scout mission scenarios

MER
Stereo-vision is selected as sole 3-D sensor for rover mission. *Evolved versions of software remains essential for MSL and Mars2020*

Mars Pathfinder
Fast mapping enabled of terrain around lander; mission planning critical

“Robby”
100M traverse by Mars rover testbed

ARL DEMO III
Maintained core competency in real-time stereo vision for autonomous navigation
Robotics Tech used for Rovers

Visual Odometry, Slip Checks, VO Auto
Dense Stereo Vision
Autonomous Terrain Assessment
AutoNav and Guarded Driving
Local and Global Waypoint Planning
Multi-sol Driving
Visual Target Tracking
Simulation
Rover Sequencing and Visualization
Terrain Classification
Autonomous Image Interpretation for Science
Autonomous Fault Response
Velocity-controlled Driving
Precision Arm Placement
Percussive Drill
Cached Sample Manipulation

...
Using visual odometry, the rover constantly compares pairs of images of nearby terrain to calculate its position.

Unlike terrestrial robots, Curiosity drives as far as possible between VO images.
Why We Need VO: Unpredictable Slip

Looking back at “Wopmay” and two weeks of challenging drives. Opportunity Sol 272
VO Enables Fewer Approach Sols

VisOdom enabled 8 meter 1-sol approach on 20-24 degree slope
Visual Odometry Benefits

Visual Odometry Increases Science Return

- Provides robust mid-drive pointing; even if you slip, the proper target can still be imaged
- Enables difficult approaches to targets in fewer Sols; drive sequences conditional on position

Visual Odometry improves Rover Safety

- Keep-out zones; if you slide too close to known hazards, abort the drive
- Slip checks; if you're not making enough forward process, abort the drive
Onboard Dense Stereo: Spirit’s Navcam
Curiosity has 17 cameras

However, only the Hazcams and Navcams are tied into the auto-nav software.
The hazard avoidance cameras give a 120° wide angle view of the area near the rover. Front cameras have 16cm baseline, rear cameras have 10cm baseline.
The 45° navigation cameras are almost 7 feet off the ground with 42cm baseline, providing good views over nearby obstacles or hills and into ditches.
During nominal auto-nav, the rover stops every 0.5-1.5 meters, takes 4 sets of images, evaluates hazards, and then chooses where to drive.

Auto-nav extends directed drives into previously unseen terrain.
The rover reduces a stereo point cloud into a configuration space, labeling unsafe areas red and safe areas green. Engineers have told the rover to stay within the white area. Yellow means drive carefully, just like on Earth.
Watch “Rover Navigation 101” online for deets.
Wheel tracks after the first auto-nav drive on sol 372 show that Curiosity chose to drive around a little mound of loose rock.
Curiosity’s map and tracks show this decision to turn was based on her evaluation of the terrain.

Curiosity avoids the darker orange in favor of yellow.

The resulting turn
Animation of Curiosity’s actual Sol 372 drive over a picture of her tracks
Spirit Sol 106: Avoiding a 21cm rock
Spirit Sol 107: Avoiding Rock Pile
D* Global Planner in the lab

Overhead Imagery

Field D* Cost Map

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D* Global Planner on Opportunity

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D* Global Planner on Opportunity
Curiosity Sol 431: Avoiding Rocks
Curiosity Sol 431: Avoiding Rocks

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Curiosity Sol 436-437: Multi-sol Drive
Opportunity Drives through Sol 410

Driving Modes:
- Blind
- Autonav
- Visodom

Endurance Crater
PanPos3

Heat Shield

Fram Crater

Eagle Crater

North

Sol 410

100 meters

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Spirit Drives through Sol 418
Visual Target Tracking

Sol 743
Sol 923
Sol 967

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Data from the Mars Reconnaissance Orbiter helps “see” several kilometers ahead, allowing for long term planning.
Autonomous Science: AEGIS

Autonomous Science processing now performed onboard: automatic detection of Dust Devils and Clouds

Conserves downlink bandwidth, transmitting only those data known to be interesting
Autonomous Arm Placement: Spirit

Rover Exclusion Zones

High resolution terrain model processed onboard

Potential IDD Placement targets

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A previous day’s images are fed into the Rover Simulation Visualization Program (RSVP) and 3D meshes are created.

Rover drivers wear shuttered 3D goggles to view stereo imagery and 3D meshes.
The Rover Simulation Visualization Program (RSVP) projects simulated drives into all available images.
For “directed driving,” drivers command the rover to move a certain distance over ground that they know is safe.

This is the fastest way to drive, because no predictive hazard processing is done, but distance is limited by what people can see. Curiosity will always stop the drive if a fault is detected!
Curiosity Lets Human Drivers Choose the Level of Autonomy on Each Drive

Visual odometry, or Slip Check + “Auto”

Auto-navigation; Geometric Hazard Detection and Avoidance

Directed driving

Visual Target Tracking
Unexpected Challenges!
Sol 122: VO vs IMU

• By convention, any VO updates that measure more attitude change than the IMU does will be rejected; we tend to trust the IMU, especially over short distances.

• On Sols 122-124, Curiosity drove using Visual Odometry (VO), but several VO updates were rejected!

• Turned out that VO was right! A parameter caused the IMU gyro-based attitude estimator to reject changes under high accelerations.

• No more issues since updating that parameter.

• VO updates have failed to converge just 34 times out of 10,086 attempts as of sol 1294, and only 14 times for actual lack of texture; 99.86% success rate!
On sol 455, Curiosity Tried Multi-sol Driving again

• Multi-sol driving succeeded on sols 435-436!

• But the second try was halted by a drive stall, and interesting D* behavior on the first day, sol 455.
A Rover’s-eye view of the Autonomous Portion of the sol 455 drive
Then, boxed in by Keepin Zones, D* tried backtracking!
On sol 455, Curiosity encountered a small crater and began to drive around it.

Small light blue dots represent the imaging steps.
Sol 535: Climbing Over
Statistics through sol 1330
Curationity Odometry Per Sol

Curiosity Odometry Per Sol by Drive Mode

Drive Distance Per Sol (Meters)

Sol

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Curiosity Cumulative Odometry

Curiosity Cumulative Odometry by Drive Mode

Cumulative Drive Distance (Meters)

Sol
Some Sojourner Onboard Capabilities

- Stereo Vision-based Obstacle Detection and Avoidance
  - 5 laser light stripes, processed at 4 locations for 20 samples
- Find Rock
- Thread the Needle Driving
- Fault Recovery
Some MER Onboard Capabilities

• Primary Mission
  – Local Path Selection
  – Dense Stereo Vision for ...
  – ... Terrain Assessment
  – AutoNav: Hazard Detection and Avoidance
  – Visual Odometry

• Extended Mission Proposal Included Research Infusion
  – Global Path Planner - Field D*
  – Visual Terrain Tracking
  – Autonomous Science, e.g. Dust Devil / Cloud Detection
  – Autonomous Instrument Placement
Some MSL Onboard Capabilities

- Primary Mission
  - Local Path Selection and Global Path Planner - Field D*
  - Dense Stereo Vision for ...
  - ... Terrain Assessment
  - AutoNav: Hazard Detection and Avoidance
  - Visual Odometry
- Post-landing FSW updates
  - Visual Terrain Tracking
  - Autonomous Science – e.g., Dust Devil / Cloud Detection
What’s Next is up to You!

• Technology transfer into flight has several paths

• People: Join a flight project to support tech transfer

• Tech Push: MER 4\textsuperscript{th} flight software release was coordinated as a tech transfer push by Project and Line Management

• Tech Pull: Anomalies are opportunities!
Navigation FGPA Coprocessors

Robots Development: Terrain Relative Navigation & Mars Rover Fast Traverse

Terrain Relative Navigation (TRN) for Precision Landing in Planetary Exploration

New Millennium Program (NMP)
Pre-phase A study of pinpoint landing and landing hazard avoidance, which included a concept for an FPGA-based coprocessor to accelerate machine vision algorithms, and phase A, which culminated in a sounding rocket-based demonstration in 2006 of machine vision-based terrain relative navigation for pinpoint landing.

Army
Expanded core competency in image processing for terrain classification

Table: 2002-2003
DARPA
Started FPGA implementation of stereo vision algorithms for collision avoidance and safe landing of micro air vehicles

Table: 2004-2006
JPL – R&TD
2007-2009 R&TD on FPGA implementation of visual detection, feature tracking, and stereo vision enhancement

Table: 2009-2011
DARPA & Army
Maturation of FPGA-based stereo vision

Table: 2011-2015
JPL – R&TD
2011-2013 R&TD extended FPGA-based machine vision acceleration for “rover fast traverse”

Table: 2016
ALHAT
Continued development of autonomous landing hazard detection and avoidance

Mars 2020
TRN and rover fast traverse baselined for the M2020 mission

FPGA Coprocessor for Fast Machine Vision for Autonomous Rover Navigation

NASA/JPL-Caltech

Courtesy Larry Matthies

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The Road Ahead
Targets for Exploration

Sulfate Unit (8 km)
Hematite Ridge (5 km)
Clay Unit (6 km)
Paintbrush Unit (2 km)