Experiences with Waypoint Navigation in Planetary Exploration and DOD Applications

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Waypoint Navigation

Computer Aided Remote Driving (CARD)

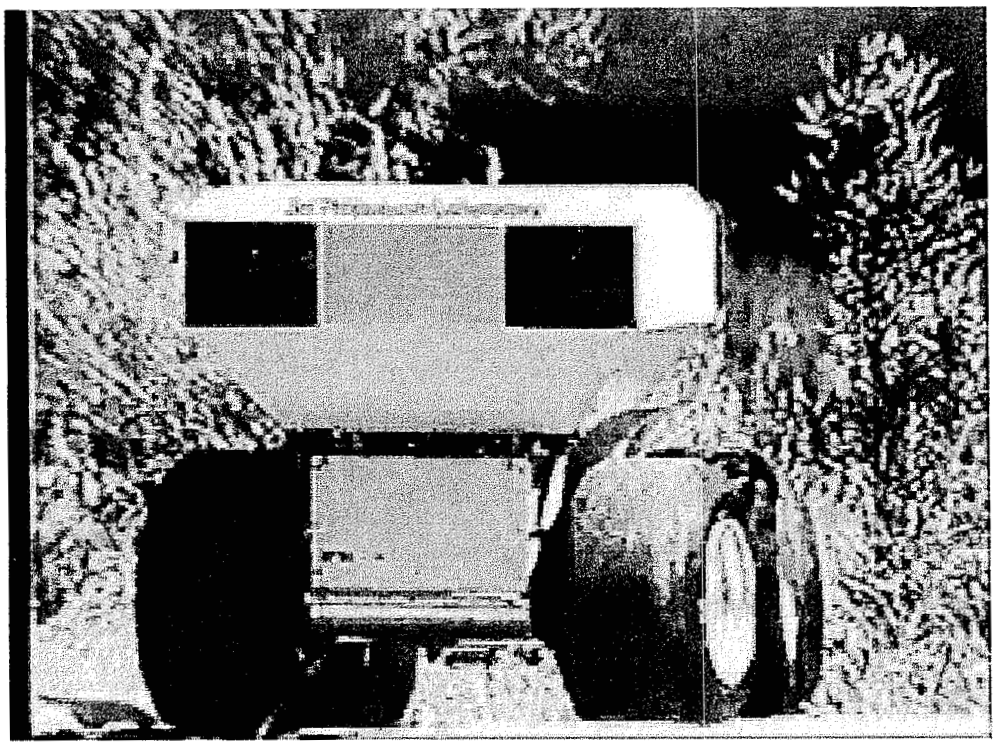
- Operator designates planned vehicle path via waypoints projected onto image of scene ahead of vehicle
- Stereo images often used (but not essential) to allow 3-D positions of waypoints (and turn angles and distances) to be computed directly
  - flat Earth assumption often used (with pitch and roll sensor data feedback)
  - vehicle can recover range to points using direction vector and range sensor
- Vehicle traverses designated path
  - combination of dead reckoning, inertial navigation
  - "reactive" hazard avoidance
  - sensor-based termination conditions
- Cycle repeats

Development History

- Conceived by this author Dec '82 as part of study for U.S. Army Engineer Topographic Lab (Bruce Zimmerman)
- Proposed to and developed for TACOM from '83 to early '90s (Jerry Lane, Charles Beaudette, Paul Lescoe). Used in Demo 1.
- Developed as part of NASA planetary rover research program leading up to Sojourner mission ('87-'93)
- Used as primary means for controlling Sojourner on Mars (Summer '97)
- Planned as primary means for controlling twin Mars Exploration Rovers (Winter/Spring '04)

Waypoint Navigation - The Early Days ('83-86)

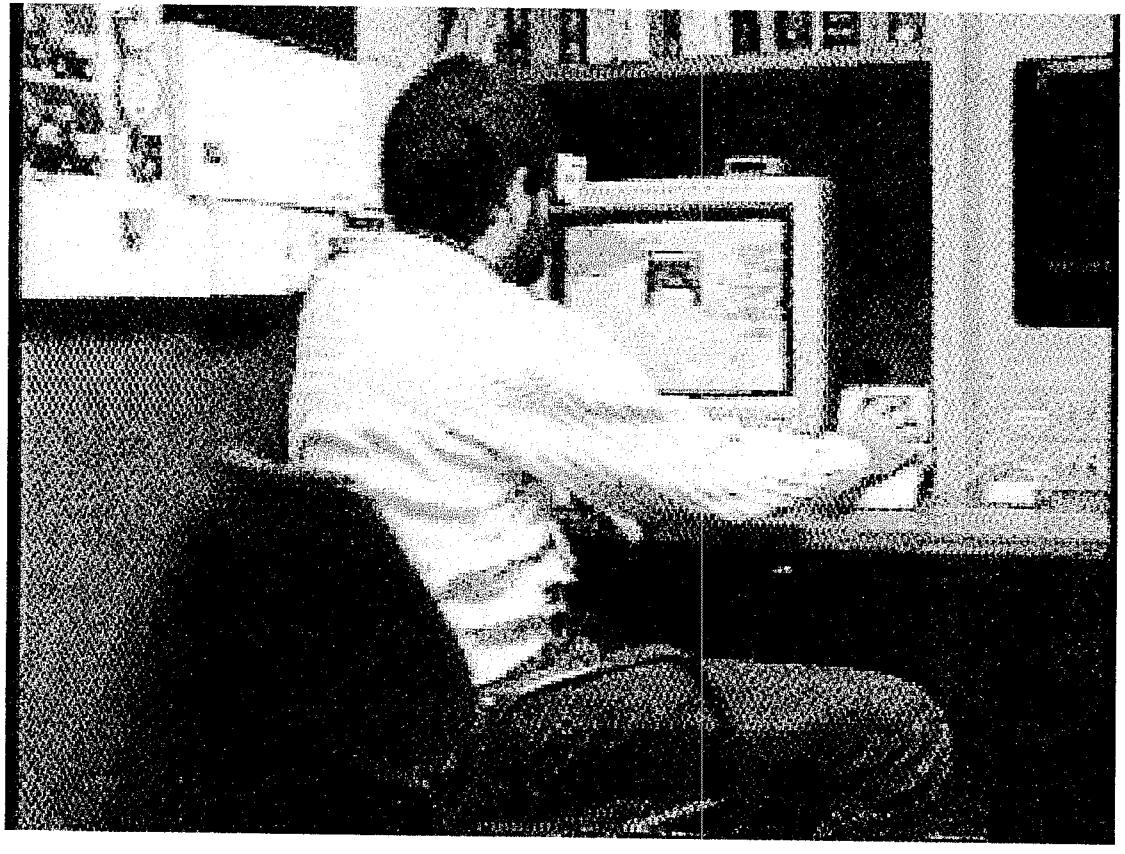
(Running Time 1:58)



- Stereo cameras mounted on passively stabilized platform
- Images projected in stereo using two polarized monitors and beam splitter
- Operator uses joystick to move cursor along virtual ground plane, 3rd control for out-of-plane
- Real time tracking of visual features to augment dead reckoning
- No hazard avoidance

Putting CARD on a HMMWV

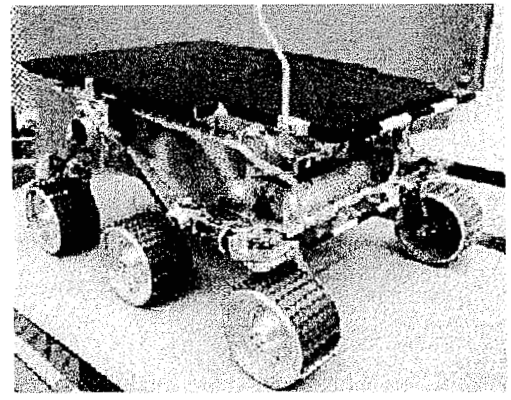
(Running time 0:25)

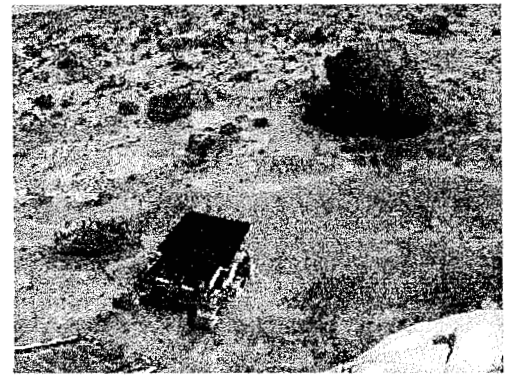


- Extensive field tests Summer '88 at Edwards AFB.
- Demonstrated CARD over SINGARS non-LOS radio link.
- Takes 3 to 10 seconds to designate 100 m path, depending on scene complexity.
- No on-board hazard sensing and avoidance at that time.

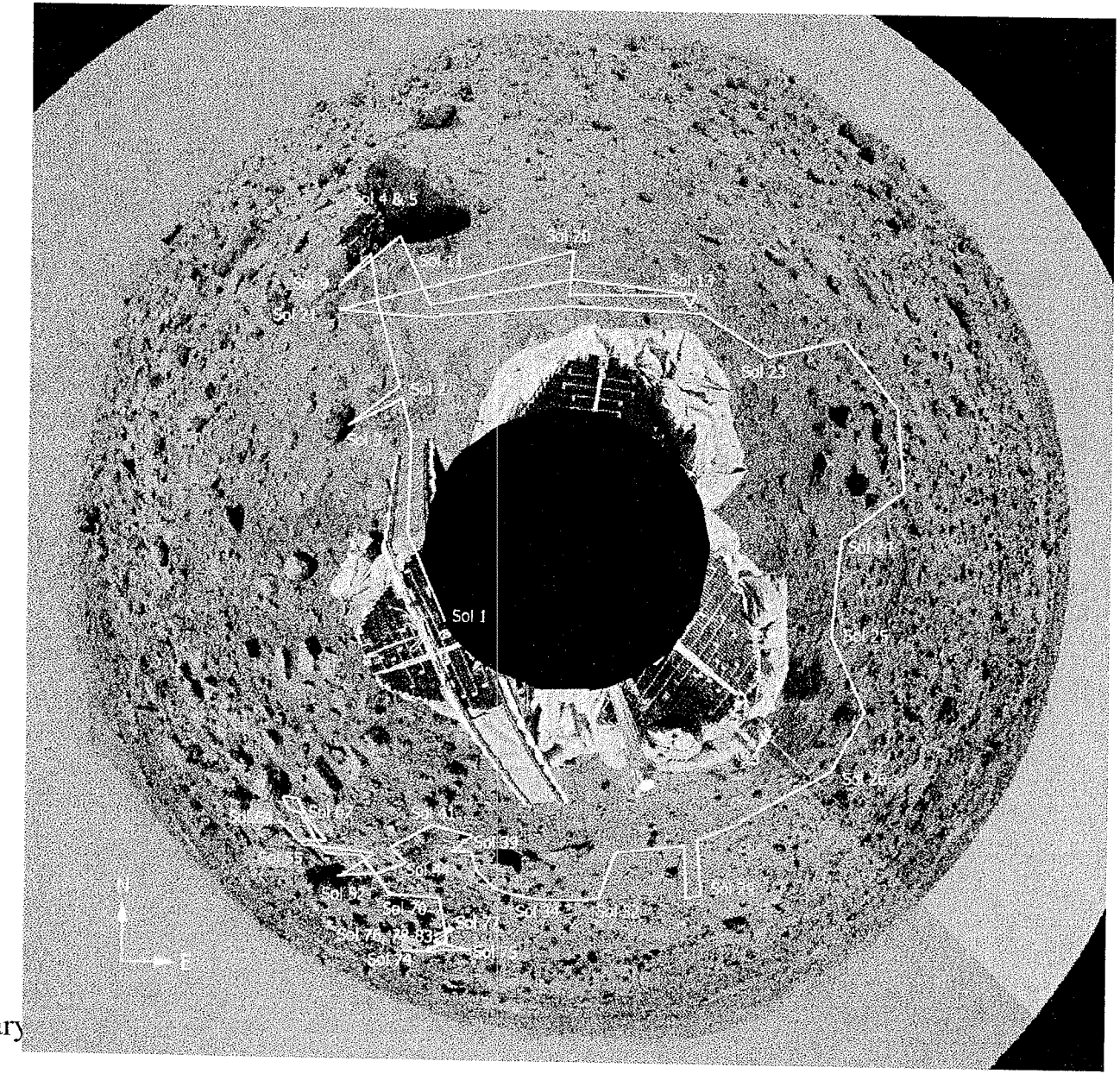
Sojourner on Mars

- Landed 4 July 1997
- Operated 83 Mars Days (Sols) until lander-Earth communications lost
- Controlled using waypoints designated over panoramic stereo images taken by lander
- Autonomous hazard avoidance using 5 laser light stripes projected on ground and seen by on-board stereo cameras



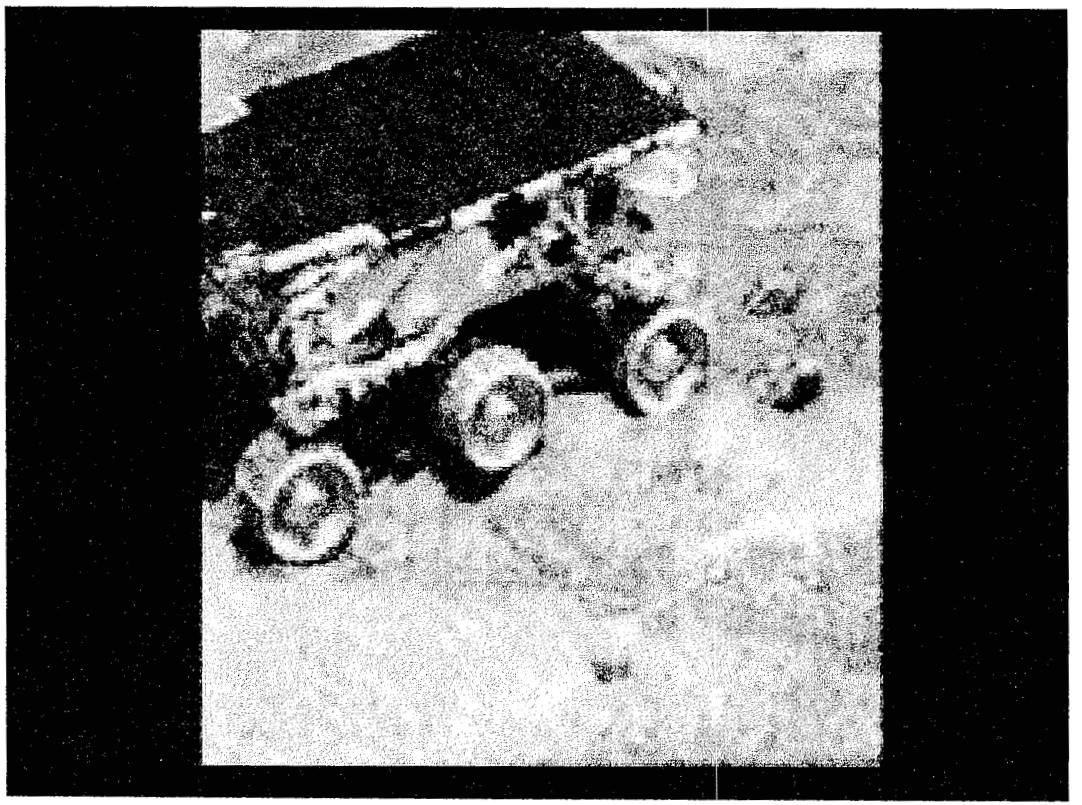


A Top-Down View of Sojourner's Traverse on Mars



Waypoint Designation with Sensor-Based Termination (Find Rock)

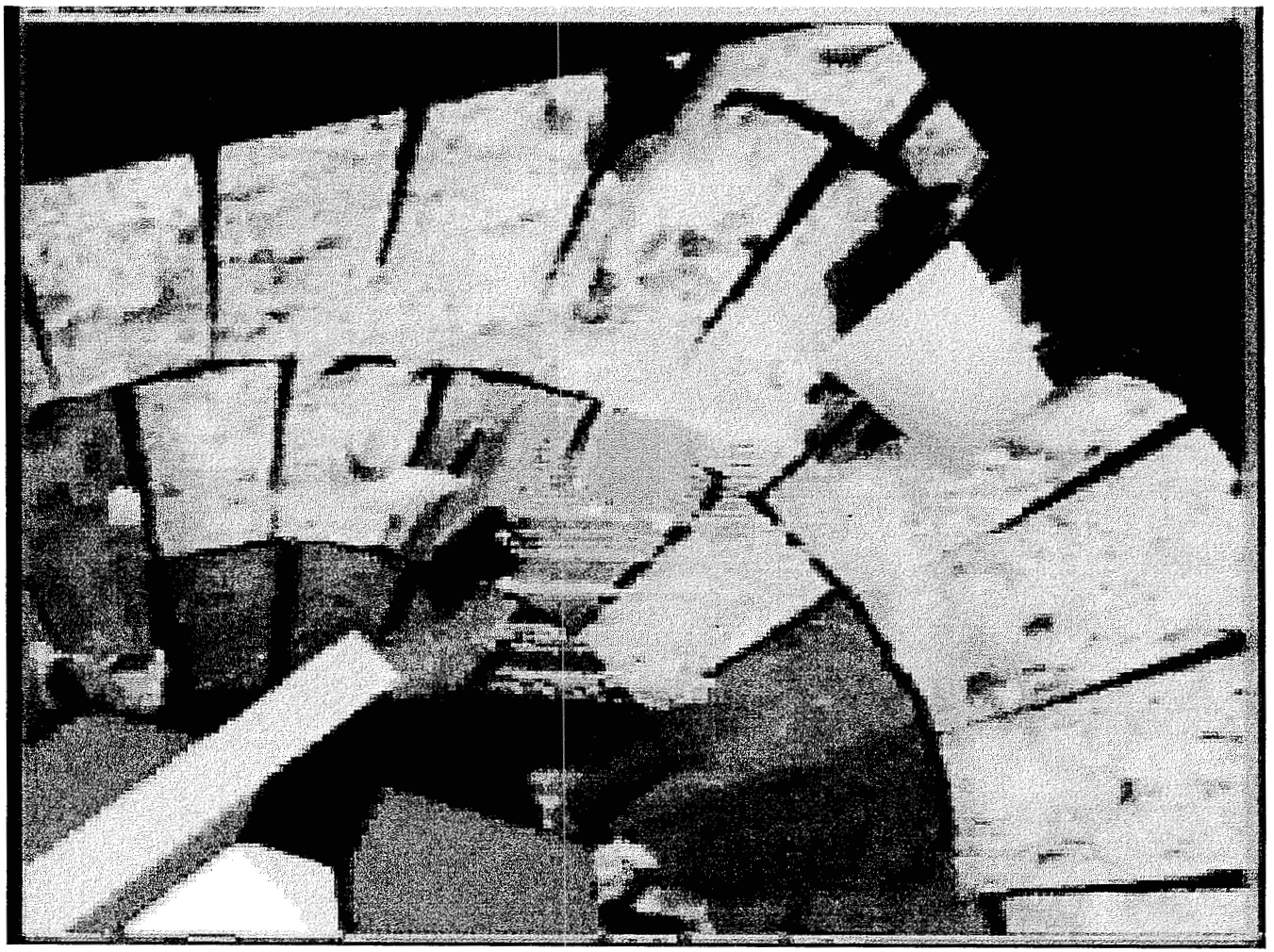
(Running time 0:25)

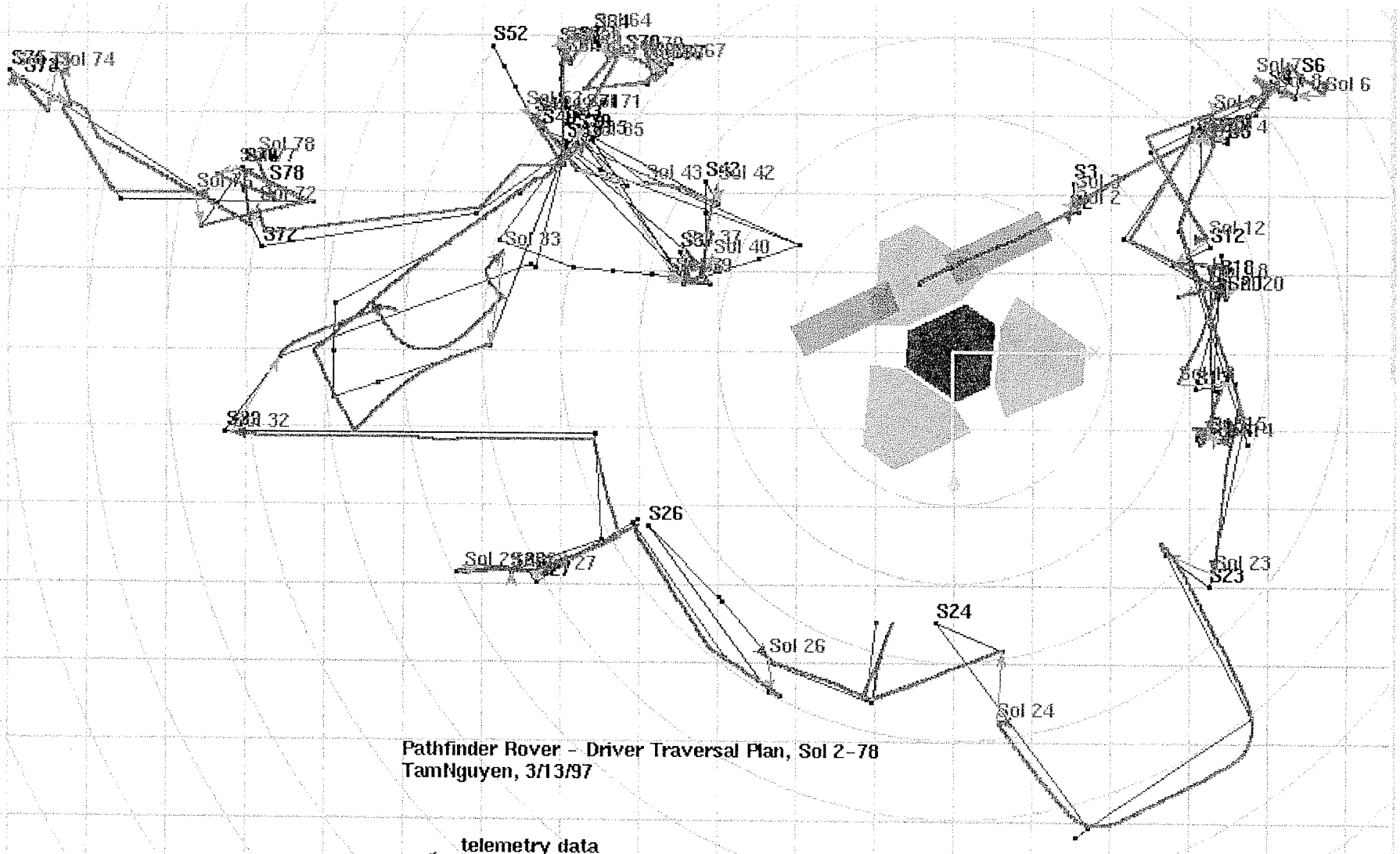


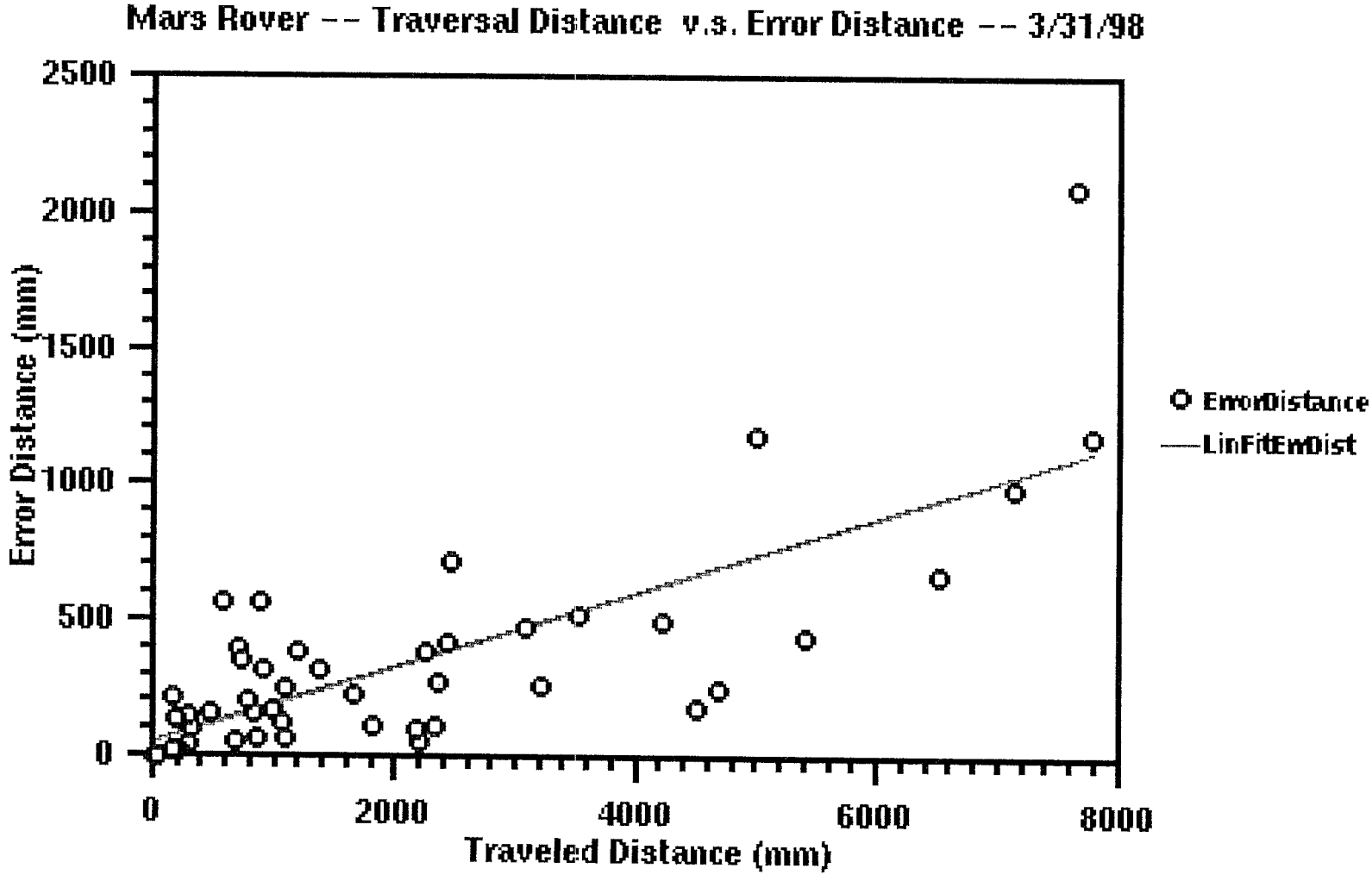
- A traverse with 3 waypoints designated, with last one identified as "find rock"
- Laser stripe range sensor used to center rock in front of vehicle instead of avoiding it.

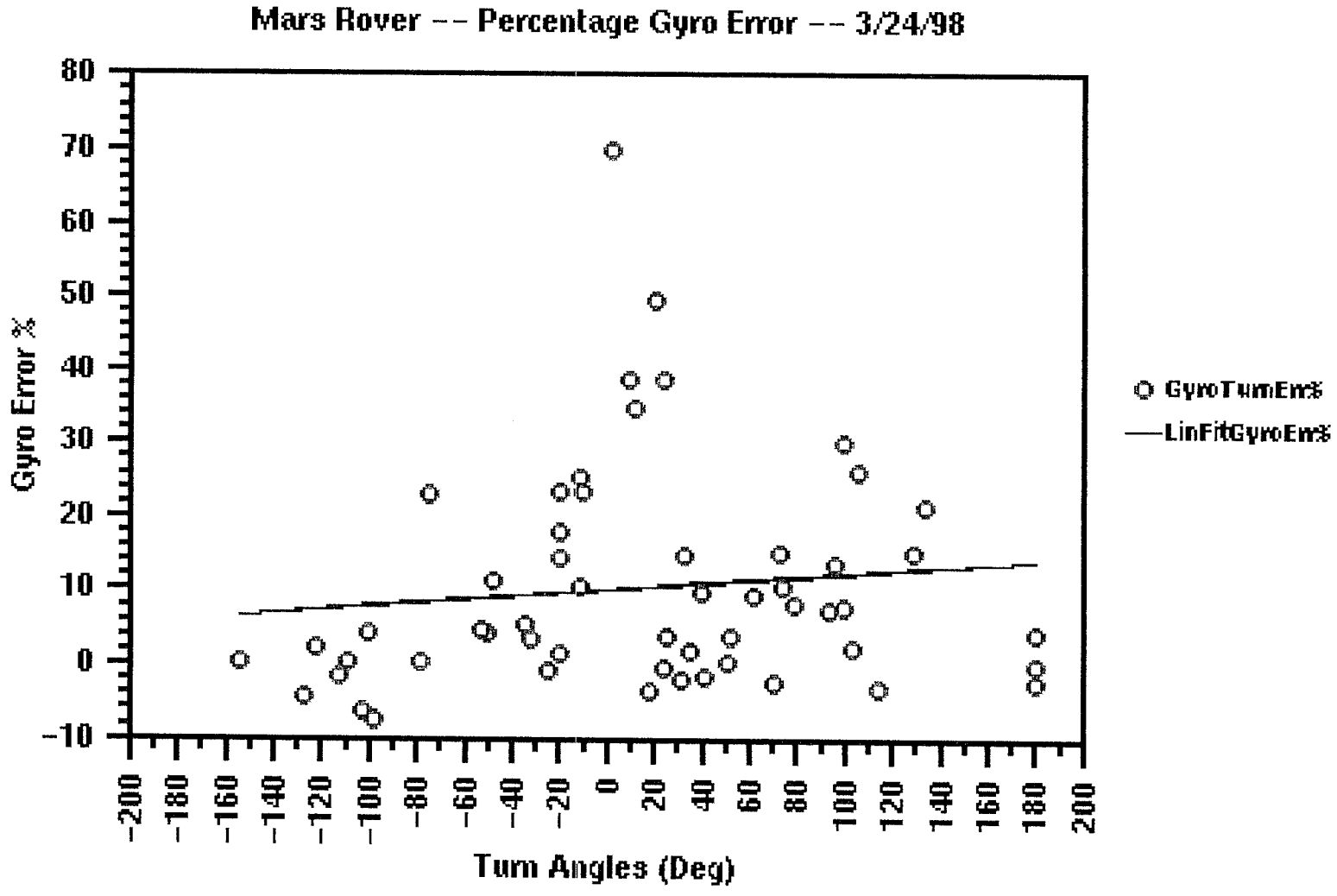
Sensing for Path Termination and Avoiding Hazards

(Running Time 2:45)




S52
S78
S77
S26
S24
S23
S12
S3
Sol 74
Sol 78
Sol 43
Sol 42
Sol 40
Sol 33
Sol 32
Sol 26
Sol 24
Sol 23
Sol 12
Sol 6
Pathfinder Rover - Driver Traversal Plan, Sol 2-78
TamNguyen, 3/13/97
telemetry data
telem sol connections
driver designated path
designated destination
sol connections


Mars Rover -- Traversal Distance v.s. Error Distance -- 3/31/98
Error Distance (mm)
2500
2000
1500
1000
500
0
0
2000
4000
6000
8000
Traveled Distance (mm)
ErrorDistance
LinFitErrDist


Mars Rover -- Percentage Gyro Error -- 3/24/98
Gyro Error %
80
70
60
50
40
30
20
10
0
-10
-200
-180
-160
-140
-120
-100
-80
-60
-40
-20
0
20
40
60
80
100
120
140
160
180
200
Turn Angles (Deg)
GyroTurnErr%
LinFitGyroErr%

Waypoint Navigation for DOD Applications

- Reduced Crew-Sized Vehicles
  - Designate path, rely on sensing for safe traverse, watch over during execution (while looking for threats and targets)
  - Use termination conditions such as "in treeline", or "behind building"
  - Crew becomes familiar with performance of autonomous system and can calibrate what terrain and speeds give good performance
  - Designate on heads-up display directly over scene for full resolution
  - Vehicle range sensor recovers accurate 3-D positions of waypoints as they are designated - no need for stereo cursors or 3-D joysticks
  - Inertial drift only accumulates for one designation cycle

Waypoint Navigation for DOD Applications (con't)

- Low Bandwidth alternative to Teleoperation, and allows greater involvement of "human intelligence" than more autonomous systems
- Other possible roles:
  - precise positioning of air-dropped assets into "binocular defilade" vantage points giving desired overwatch
  - single waypoint plan can be made for multiple vehicles to convoy along route
  - pre-designated escape or recovery routes for teleoperated vehicles if communications is lost

Summary and Conclusions

- Waypoint Navigation has been proven over nearly 20 years in DOD and NASA research and is the baseline for NASA Planetary Exploration program.
- Adding advanced computer algorithms WITH HUMAN APPROVAL AND/OR OVERSIGHT for
  - reactive hazard avoidance,
  - feature tracking,
  - road following, and
  - sensor-based termination conditions, etc.

  makes reliance on pure dead reckoning less risky.
- Has tremendous potential as a way to manage workload on Reduced Crew-Size Vehicles and other DOD applications.