DARPA's LAGR and UPI Programs

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LAGR hHerminator

UPI "Spinner"

UPI "Crusher"

Operation in Unstructured Environments

Desired Characteristics for UGVs

- Autonomous operation over many km, beyond line of sight (no human intervention)
  - We are making progress
- Safe operation near people and other vehicles
  - Just starting to be addressed
- Graceful fallback to human teleoperation when autonomous operation fails
  - Often not possible because of comms limitations
    - Guestimates of required comms-
      - Simple environments (e.g. road with no traffic) - at least 1Mbps < 100 msec latency to maintain vehicle speed
      - Complex environments (city driving, off road driving) at least 10Mbps perhaps 1Gbps < 30 msec latency

➔ We need to make autonomy work

How autonomous navigation is done today

Sense the environment, usually with LADAR
    Useful range is typically less than 50m

Create a 3-D model of the space with solid and empty volume elements

Identify features in the environment:

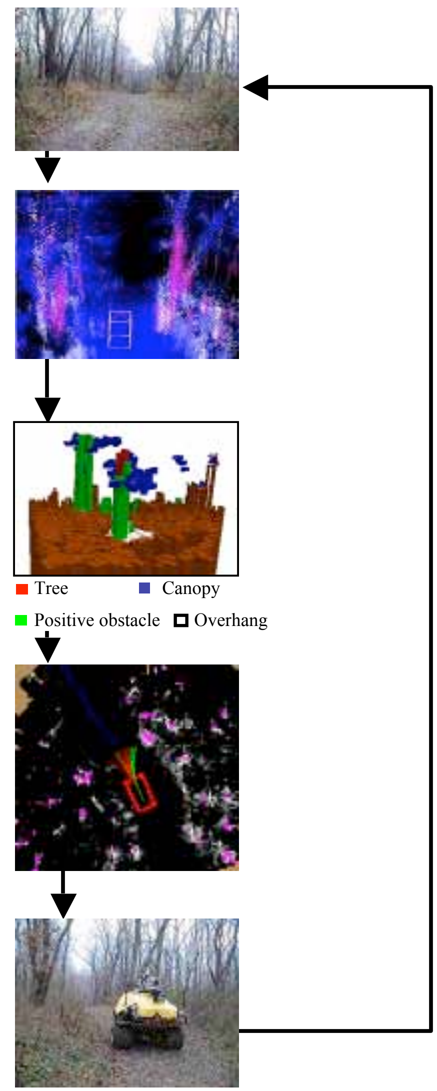
    Ditches, Grass, Water, Rocks, Trees, Etc.

Create a 2-D map of safe areas (black) and dangerous areas (red)

Run a path planning algorithm to decide on the next move toward the goal, staying in the "black" areas

Move the vehicle

Repeat



Autonomous Navigation Today

(Results from DARPA PerceptOR Program, Completed 2004)

Good performance, provided the environment is not too cluttered or complex

Performance degrades in complex environments; much worse than human RC operation

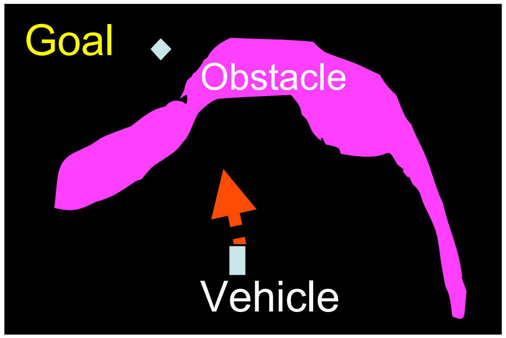
- Unreliable object recognition
- Minimal scene analysis

Too much reliance on non-adaptive, brittle, handcrafted algorithms

- No “common sense”: Generally can’t learn from mistakes

Challenges for Autonomous Navigation

- Develop robust obstacle detection
  - e.g. differentiate between rocks vs tall compressible bushes
  - Need adaptive systems that learn
- Overcome limitations of near-sighted sensing (LADAR or Stereo)
  - Avoid getting trapped in cul-de-sacs
- Determine location and orientation without high-accuracy GPS
  - Possible solution: Visual Odometry
- Scene Understanding
  - “See” the path without explicit range-finding or object recognition



Learning Applied to Ground Robots (LAGR)

LAGR Goals –

Specific:

- Advance the frontier of autonomous navigation of unmanned ground vehicles (UGVs) in complex terrain

- Tech transfer to DARPA UPI program

General:

- Advance machine vision

- Apply machine learning to a new domain

- Couple machine vision with machine learning

Problem:
How can we measure progress in UGV autonomy?

No standard hardware

- Many different UGV designs
- Pick a "standard" UGV



No *a priori* measure of the difficulty of course

- Depends on the mechanical capability of the robot and the complexity of the terrain
- "Calibrate" the course by measuring performance of baseline navigation software on the chosen standard UGV

No standard database for testing and training

- Difficult to compare results from different courses
- Measure performance of multiple systems at a specific site

DARPA LAGR Program

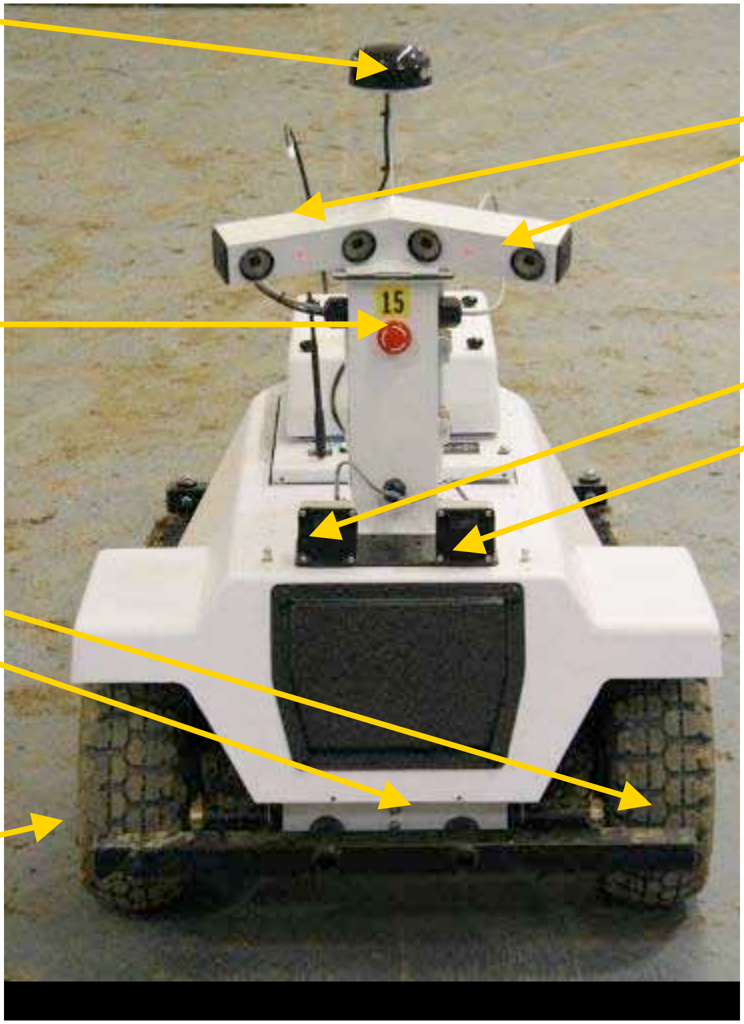
- Numerous performers, common vehicle
- Performance measured against PerceptOR baseline code
- Monthly government tests at different sites
- Encourage code sharing between performers

Bonus – shared experience among performers: a new community of interest

Applied Perception
Georgia Tech
JPL
Net-Scale
NIST
U Penn
SRI
Stanford

U Colorado
U Idaho
U Missouri
U Central Florida

LAGR Platform Front View



WAAS GPS on a collapsible mount

E-Stop

Bumper with dual limit switches

Differential drive

Dual stereo cameras

IR Range-finder

LAGR Testing

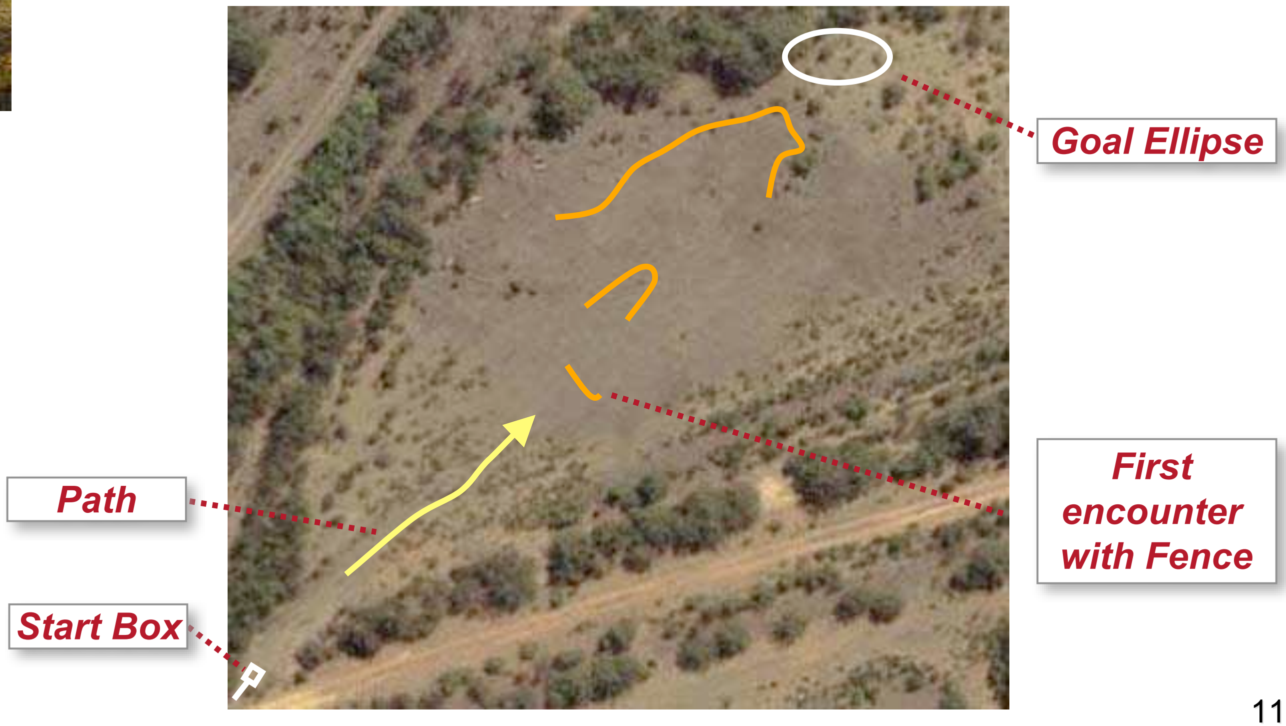
Approach

- Teams send software to DARPA test staff
- A single, GPS waypoint is specified as the goal
- Each team is given three runs using a DARPA robot
  - Learn from one run to the next – obstacle types and location
- The tests are unrehearsed, teams have not seen the course
- Teams watch and comment on tests via live video, audio, and diagnostics

As tests progressed, the Government team refined tests to isolate specific aspects of perception and navigation

Test 3 and 4 May, June 2005, Ft Belvoir

- Test designed to encourage long-range vision and planning
- Bright orange snow fences + natural obstacles
- Starting to see working learning systems
- Most systems still immature



Test 4, June 05

(video)

First evidence of long range vision

Test 5, Hanover NH Aug 05

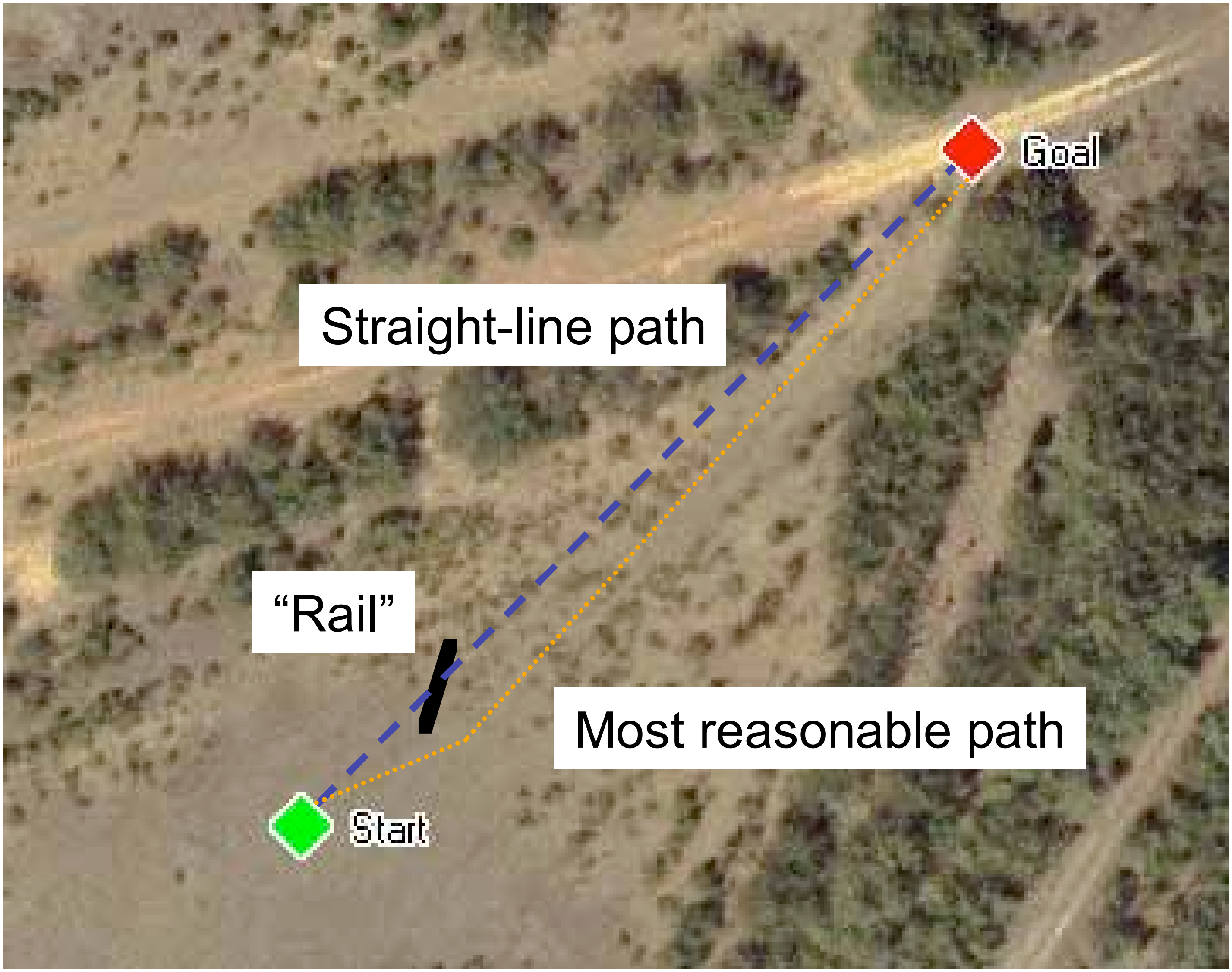
Poor GPS coverage, steep hills, lush forest

Tested trail following

Location of goal waypoint encouraged vehicle to leave trail and bushwhack though thick woods

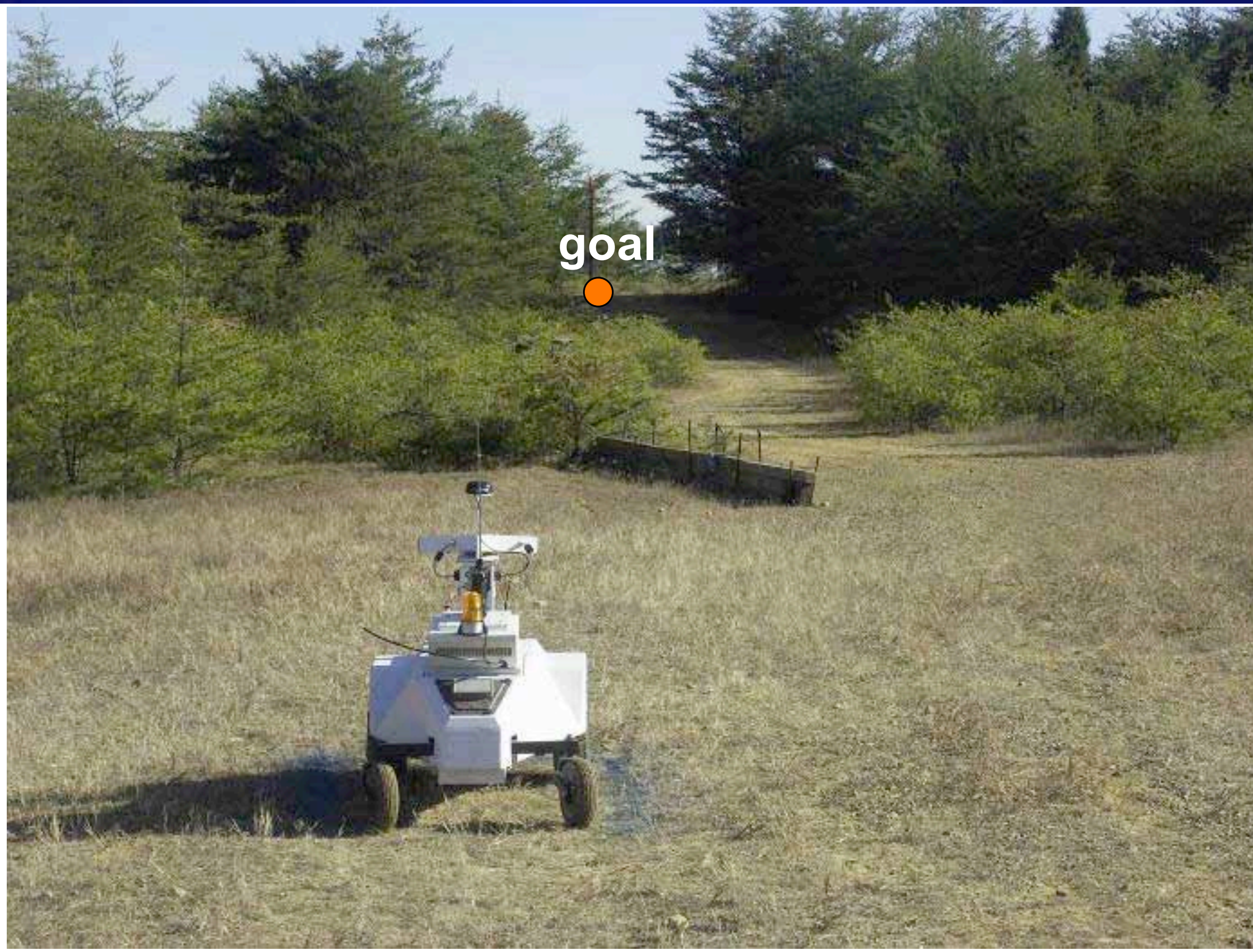
Some teams performed well

Test 7, Ft Belvoir October 05
(test of long range vision)



Some teams built orange snow fence detectors – too bad!

Test 7, Ft Belvoir October 05



Direct route to goal leads to cul-de-sac

Typical Approach to Learned Long-Range Perception

- Sense local obstacles using stereo, bumper hits, or wheel slippage
- Note optical qualities of local obstacles and non-obstacles
- Look for similar optical qualities at a distance
- Infer obstacle / not obstacle

Test 7, Ft Belvoir October 05

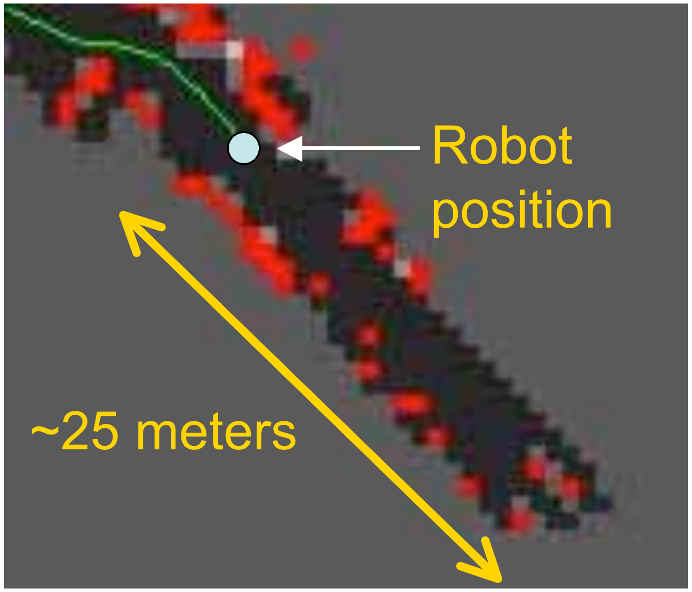
Typical behavior at the beginning of a team's first run

Most teams quickly learned that the low pines were not traversable and then successfully detected and avoided the pines at long range

API & NIST Test 7

NIST:
A neural net maps feature vectors to terrain cost at distances up to 28 m

API : Color is indexed to 3-D features that in turn indicate cost



API Cost map

Test 8, November 05, Ft Belvoir

Learning From Example

Training data:
Logs of vehicle teleoperated following white line

Results:
3 teams followed the line in Test 8, only one (API) succeeded without hints from programmers

Test 9, December 05, San Antonio TX

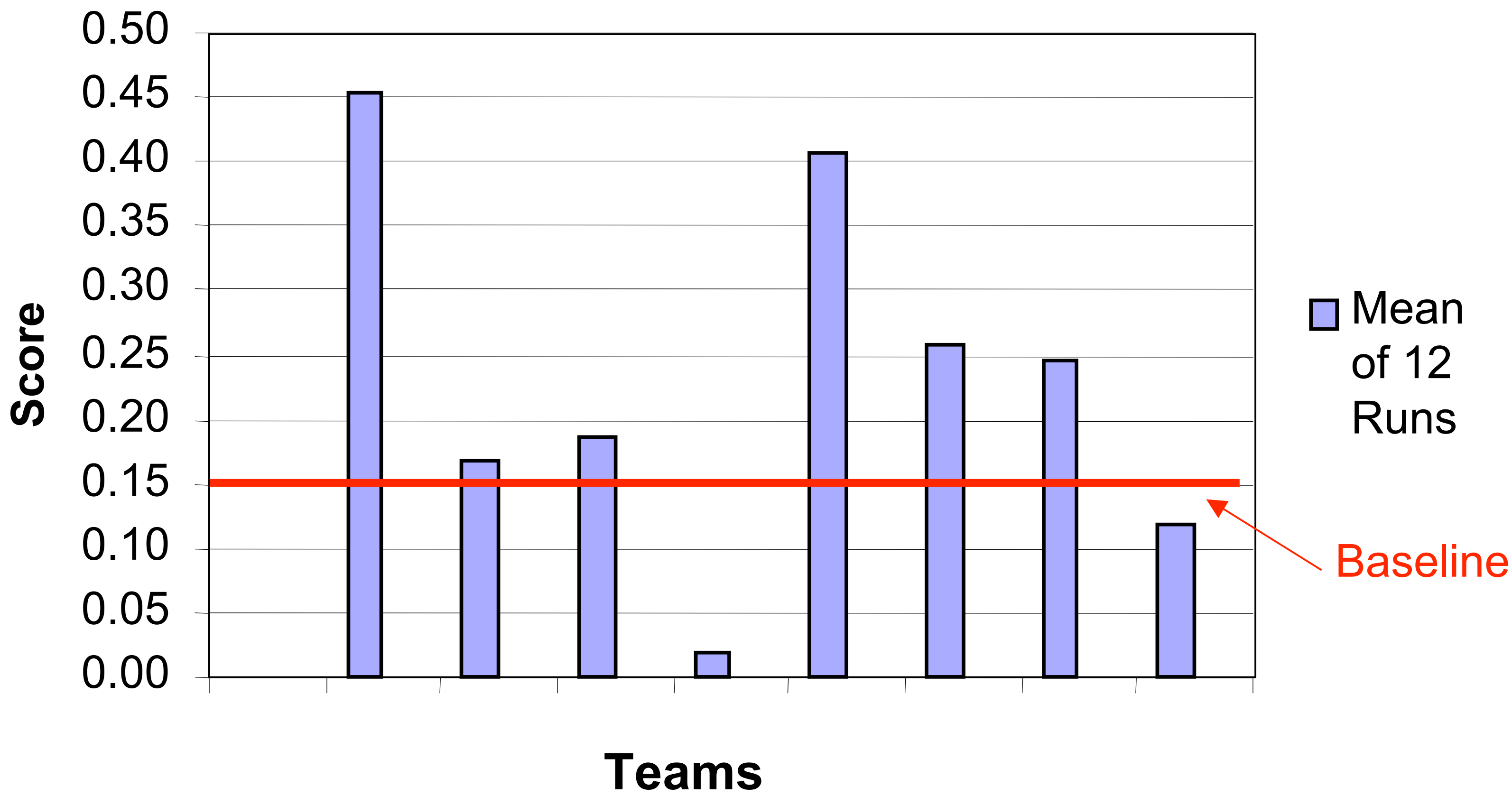
Navigation along path through dry scrub

- minimal color cues
- some teams now performing much better than the Baseline

Goal

Start

Score Statistics Tests 4, 6, 7, 8



Score = minimum possible time to complete course / corrected time on course

corrected time = actual time if course completed
= max allowed time x fraction of course completed

LAGR Summary

Excellent progress toward achieving program goals:

- Demonstrated learning from experience and example
- Demonstrated ground classification beyond range of stereo

Tests are being designed to force (as much as possible) non-incremental solutions

- Test design is challenging
- Additional tests on mono vision, long-range vision, and learning from example in Phase I

Just scratched the surface on scene understanding

Go / No Go set for May '06 for Phase II

Port of best results to UPI in Phase II

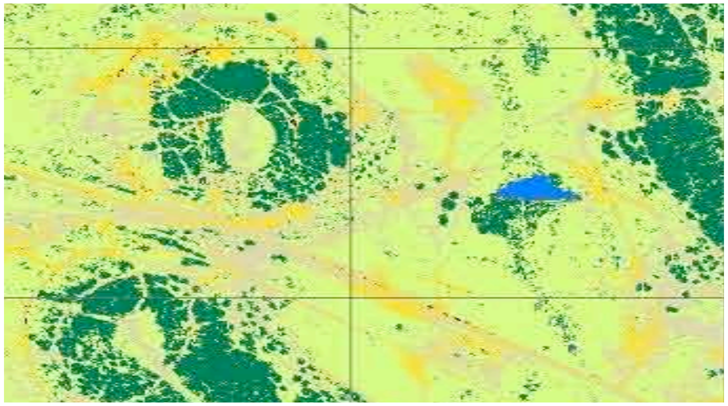
DARPA's UPI Program

Prime integrator: Carnegie Mellon University's NREC

3-year effort (ends early FY08)

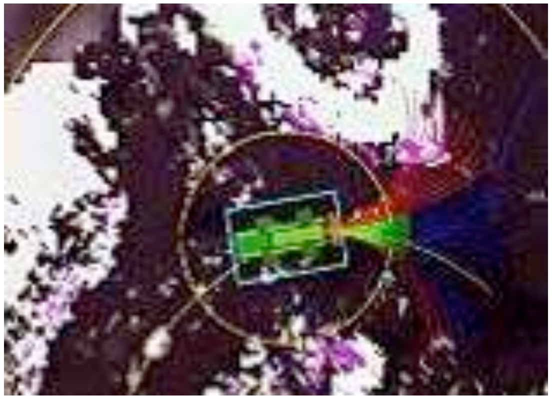
UPI Overview

Combine:



+ Prior terrain data

+ Vehicle with extreme mobility



+ State-of-the-art perception based navigation

Result:

A cutting edge system that serves as a pathfinder for large, autonomous UGVs

Obstacle Avoidance is Easier When the World Has Fewer Obstacles

Why are there no people near this robot?

UPI Status

- UPI Phase I Go/No-Go was exceeded
  - Required autonomous performance in complex terrain
    - >1.27 m/s average speed
    - < 1 intervention / 2km
  - Actual performance in test
    - 1.42 m/s average speed
    - 1 intervention in 4.5 km test course

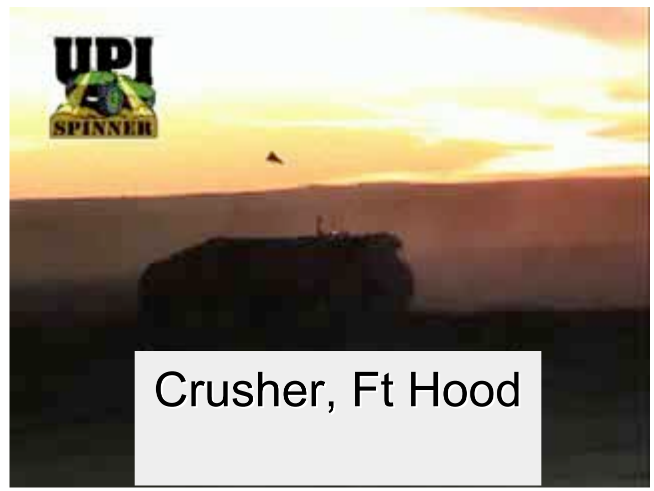
  Test was conducted the first time the vehicle was on the on the course

  No course-specific “tuning”

- 1st Crusher vehicle operational 12/05

  2nd Crusher vehicle operational 3/06

Spinner,
Yakima, Ft Hood



Crusher, Ft Hood

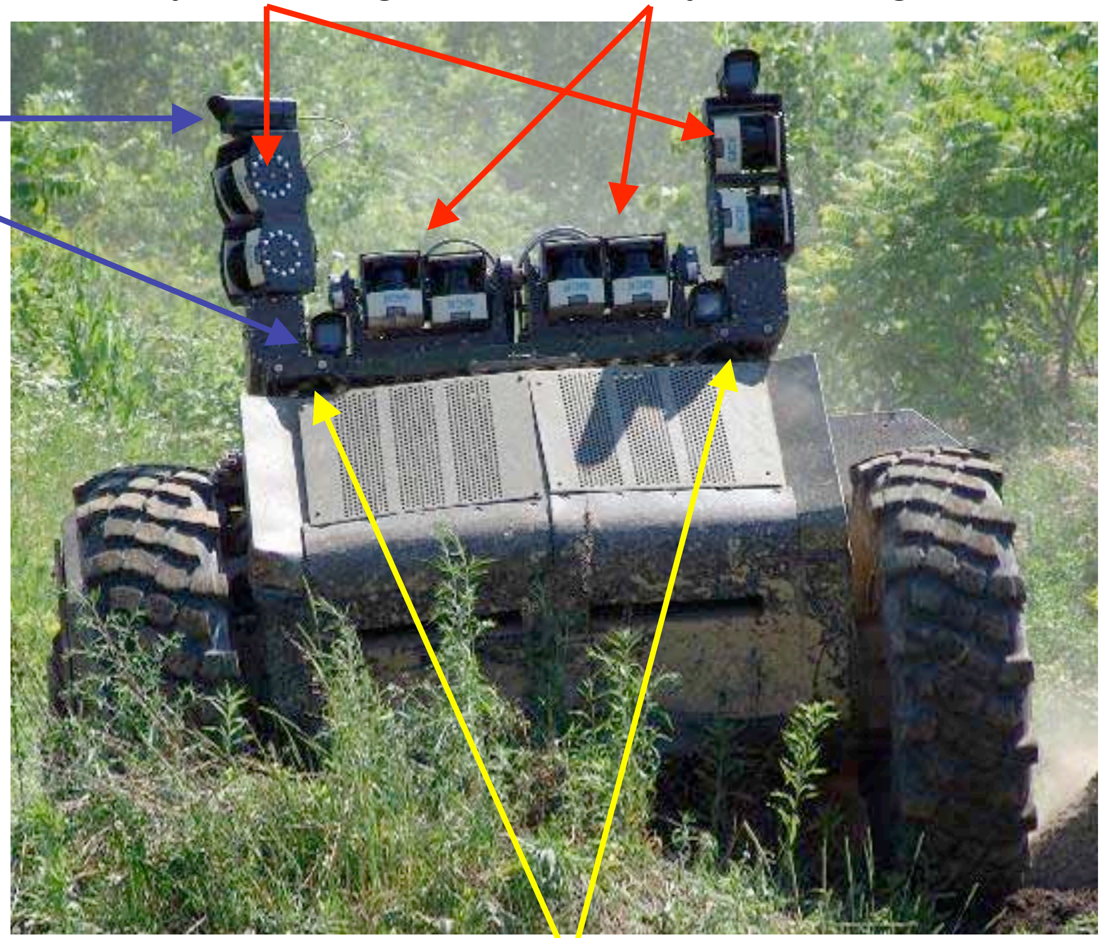
Autonomy System v1

LADAR – 8 COTS SICK LMS Units - 108 pts/sec
4 vertically scanning, 4 horizontally scanning

RGB Cameras
- Apply color pixel to each LADAR point

Novatel IMU

Autonomous Navigation Software
- Blade server used for perception processing



Stereo Camera Pairs – 6 COTS Bumblebee pairs
Identical to LAGR

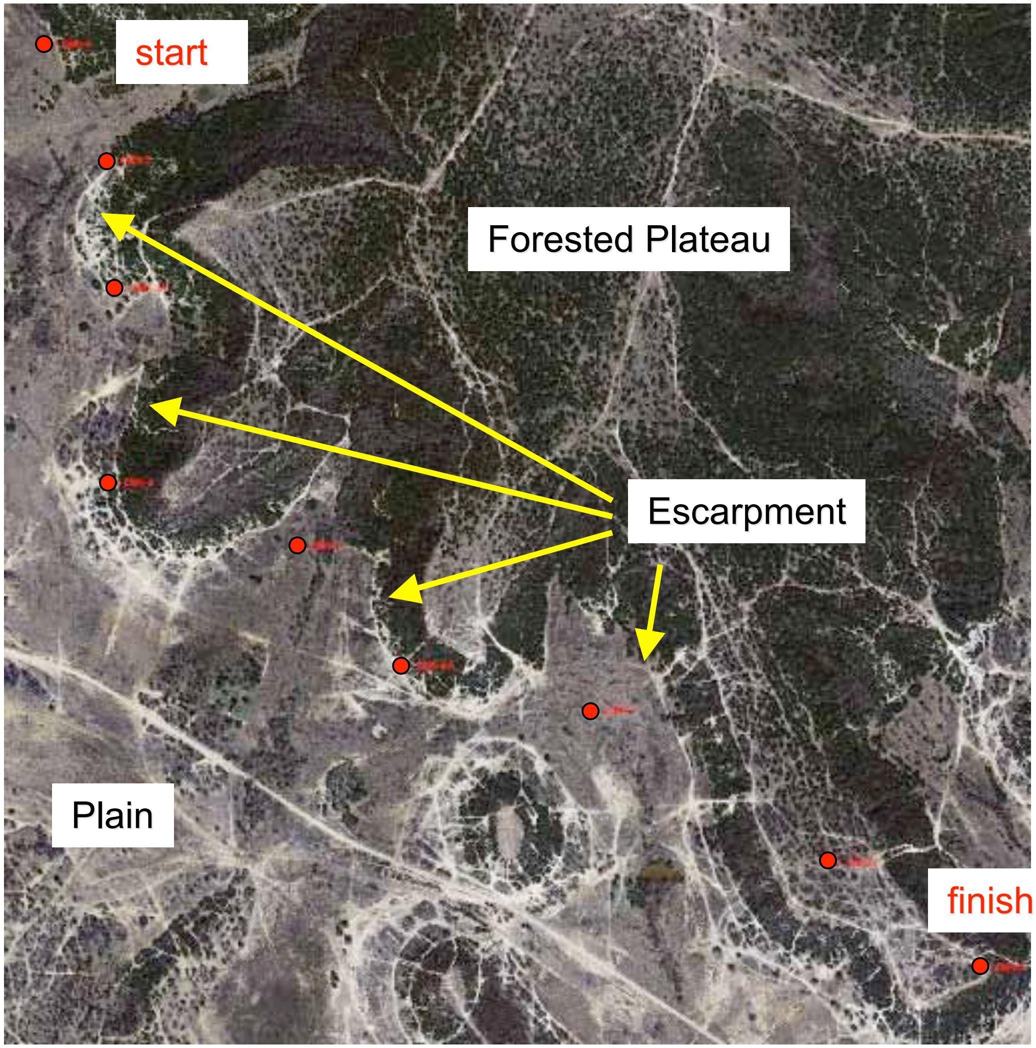
Reliability and Safety

- Deadman switch on RC control
  - Radio comms failure stops vehicle
  - No people allowed near vehicle
- Numerous vehicle “health” monitors
- Hybrid-electric drive with dual battery stacks
- Mechanical and electric regeneration braking
- 6 wheels and suspensions
  - Need only 4 to drive
- Blade server computer
- 8 Sick ladars, many cameras
- IMU + GPS
- Super tough tires
- Designed for easy repair
- Lots of spare parts trucked to field tests

Ft. Hood Test Course 1

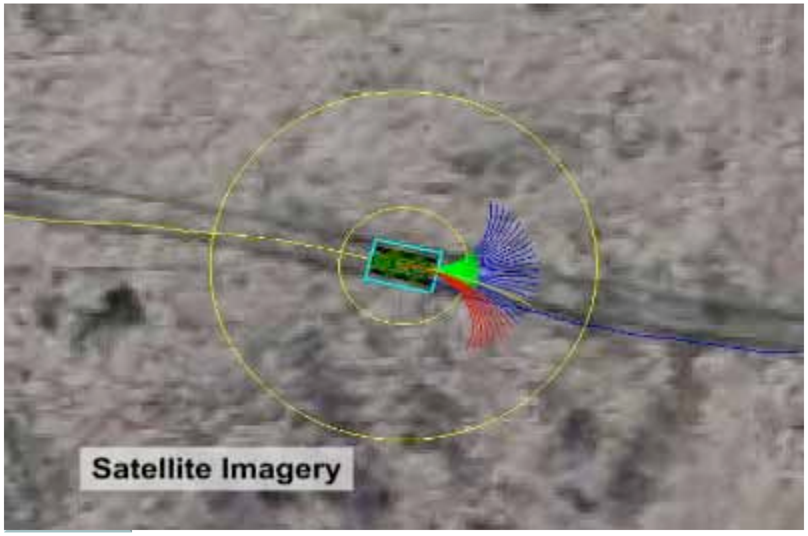
Course 1

- Nine waypoints
- Waypoint-to-Waypoint = 3.8km
- As driven by HMMWV = 4.5km
  - Follows treeline and lower contour of plateau
  - Mostly off-road with some trails
  - Many washes
  - Mixes of tall vegetation and trees
  - Climbs road at end
  - Waypoints do not allow direct point-to-point traverse
  - Higher DTED allows more aggressive planned routes

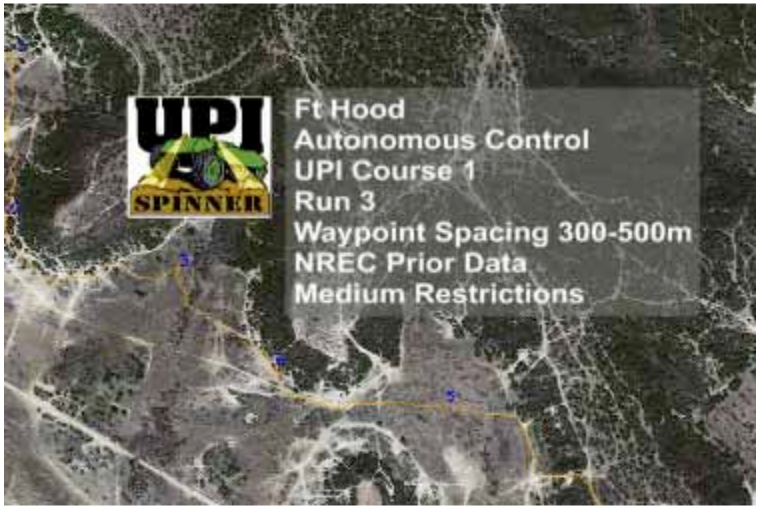


Videos from Ft. Hood

- Cost Map Example



- Course 1 Run



UPI 2.0 Vehicle – Crusher

- Completed shakeout at NREC on 25 NOV
- Tested at FT Hood –175km traveled
    - RC & waypoint following
- Base Weight – 13,000lb
    - Fuel
    - No payload, perception
    - Hybrid - 60kW turbo-diesel
- Phase II focus – Crusher
    - Autonomy port to Crusher
    - Reducing profile of sensor mast

Crusher @ Ft. Hood

UPI Plans for Phase II

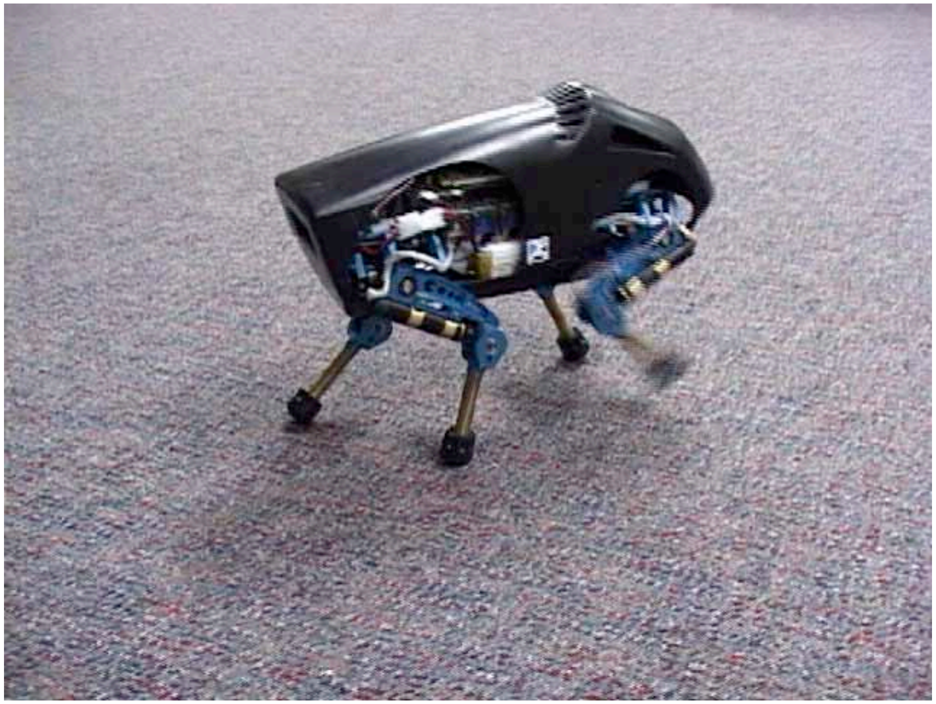
- Increase autonomous speed to > 2.5 m/s in complex terrain
- Use UPI vehicles to develop realistic requirements and operational scenarios for large, high-mobility UGVs
  - Quarterly experiments
    - June 06 - Ft. Carson, CO
    - Sept 06 - Ft. Knox, KY
- Use UPI vehicles as testbeds for new perception methods
  - LAGR

Extreme mobility + advanced perception + prior terrain data defines and expands the envelope for autonomous UGVs

Sneak Preview:

Learning Locomotion

Starts Tuesday



Decouple the control problem from the perception problem


ReproPlus
ReproPlus
ReproPlus

Summary: Building Robust Systems

- Design vehicles with high intrinsic mobility
- Use scene understanding to allow perception beyond limits imposed by range finders
- Incorporate prior GIS data to allow long-range planning
- Replace hand-crafted algorithms with learned systems
- Or: Figure out a way to have guaranteed wideband, low latency comms and a human operator available whenever needed for teleoperation
- Safety and driving near moving objects are topics for new research