DARPA’s LAGR and UPI Programs

Larry Jackel
DARPA IPTO / TTO

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
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
- Dual stereo cameras
- E-Stop
- IR Range-finder
- Bumper with dual limit switches
- Differential drive
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 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

First evidence of long range vision (video)
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
Some teams built orange snow fence detectors — too bad!
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
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.
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
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
Navigation along path through dry scrub

- minimal color cues
- some teams now performing much better than the Baseline
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
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
+ State-of-the-art perception based navigation
+ Vehicle with extreme mobility

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
    - \( >1.27 \text{ m/s average speed} \)
    - \( < 1 \text{ intervention / 2km} \)
  - Actual performance in test
    - \( 1.42 \text{ m/s average speed} \)
    - 1 intervention in 4.5 km test course
  - Test was conducted the first time the vehicle was on the course
  - No course-specific “tuning”

- 1\text{st} Crusher vehicle operational 12/05
- 2\text{nd} Crusher vehicle operational 3/06
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 ladders, 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
• 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
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
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