



Developing a Self-Driving Car for the 2007 DARPA Urban Challenge

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Urban Challenge (2007)



- Novel elements:
 - Urban road network
 - Moving traffic
 - Human and robotic!
 - No course inspection
 - 60 miles in 6 hours
 - Scored by speed, safety
 - \$3.5M prize pool
 - 89 entering teams
- Program goals
 - Safe (collision-free, polite) driving at up to 30mph
 - Capable (turns, stops, intersections, merging, parking, ...)
 - Robust (blocked roads, erratic drivers, sparse waypoints, GPS degradation and outages, ...)



Source: DARPA Urban Challenge Participants Briefing, May 2006

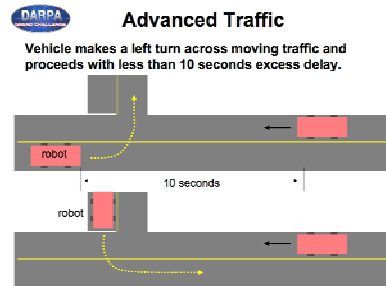


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Program Scope

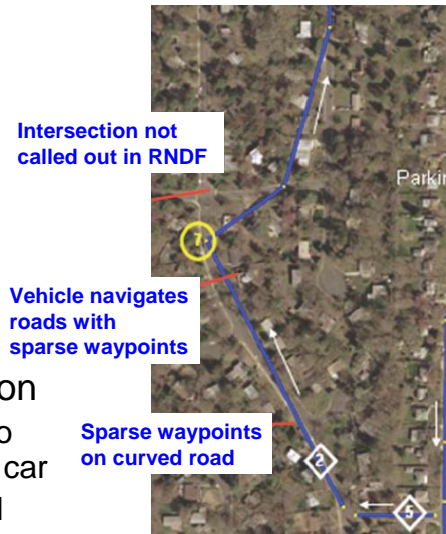
- In scope:
 - Following
 - Intersections
 - Passing, Merging
 - Parking, U-turns
 - Emergency stops
 - Timely left turns across traffic
 - Potholes, construction sites
 - Blockages, replanning

- Out of scope:
 - Pedestrians
 - High speed (> 30 mph)
 - Traffic signals, signage
 - Difficult off-road terrain
 - Highly inclement weather



DARPA-Provided Inputs

- USB stick w/ two files:
- RNDF = Road Network Description File
 - Topology of road network
 - "Sparse" GPS waypoints
 - Parking zones
 - Provided 48 hours ahead
- MDF = Mission Description
 - List of RNDF way-points to be visited by autonomous car
 - Provided 5 minutes ahead



Source: DARPA Participants Briefing, May 2006



Why tackle *this* problem?



- **Fatalities and injuries** from driving accidents
 - Tens of thousands of fatalities per year in U.S.
 - Hundreds of thousands of injuries annually
- **Productivity lost** to commuting, travel
 - Billions of person-hours per year “spent” driving
- **Energy inefficiency** of braking and idling
 - Could do much better with cooperating vehicles
- **Mandate** from U.S. Congress
 - 1/3 of military vehicles autonomous by 2015
- **Sheer appeal** of achieving a human-level capability (driving) with a robotic vehicle!



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Related Work



- **Partial Autonomous Driving Systems**
 - Limited domain (highway lane; traffic-free road)
 - Require human to: stage control handoff, monitor operation, and take over in emergency situations
 - Munich’s VaMoRs (1985-2004), VAMP (1993-2004); CMU’s NAVLAB (1985); Penn (Southall & Taylor 2001)
- **Assistive Driving Technologies**
 - Limited duty cycle (cruising, emergencies, staged parking) and actuation (e.g. none, or brakes only)
 - Require human handoff and resumption of control
 - Automakers’ ABS, cruise control, self-parking systems
 - Lane departure warnings (Mobileye, Iteris, ANU)

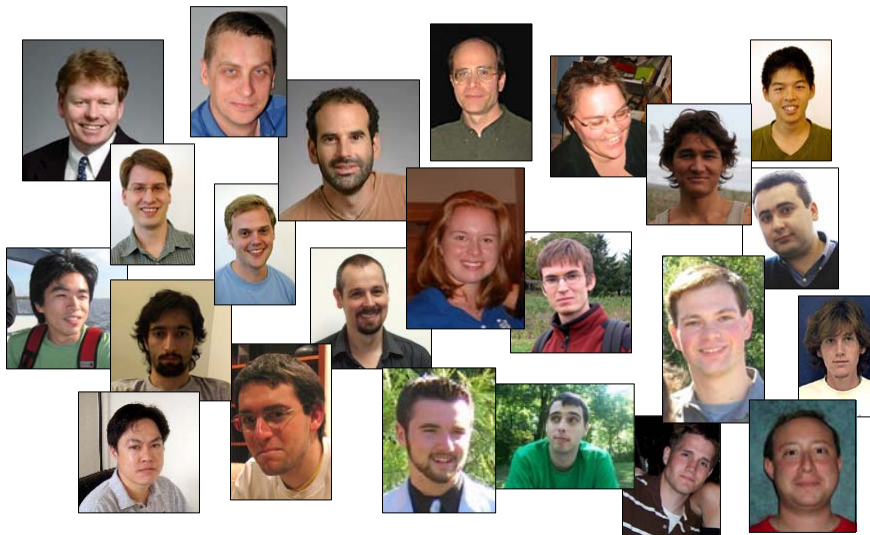



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Assessment and Strategy


- Human-level urban driving not achievable with existing algorithms / systems in 2006
 - Key issues: uncertainty; sensing/CPU resources; safety
 - Example: if vehicle is unsure where the road is, and/or where it is with respect to the road, identifying a safe, appropriate traffic behavior (at speed!) is very difficult
- Strategy
 - Technical footprint for success covers many disciplines → interdisciplinary approach integrating EECS/AA/ME
 - Spiral design approach → figure out how to solve the problem while designing the system at the same time

Team Formation




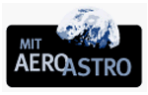



Team Members & Roles





- Faculty, postdocs, students, staff
 - Operating software, sensor & computer selection and configuration (~8 full-time graduate student programmers)
 - Project Management
- Draper Laboratory
 - System Engineering, Vehicle Integration & Test Support, Logistics Support
- Olin College of Engineering
 - Vehicle Engineering (Mech. & Elec.)
 - System Testing support
- Other Team Partners and Sponsors
 - Quanta Computer, BAE Systems, Ford, Land Rover, MIT SOE, CSAIL, EECS, A/A, MIT IS&T, MIT Lincoln Laboratory, ...





























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Compressed Timeline



- Bring up rapid prototype vehicle (Ford Escape) summer/fall '06
 - Gain experience with sensors, dynamics, coding, configuration
- Bring up competition vehicle (LandRover LR3) spring '07
 - Develop mature algorithms, tune for qualifying rounds and final event





Track A Announced (10/2)

Program Announced (5/1)

Participants Conference (5/20)


Site Visit (10/27)

2006 | 2007

Site Visit (6/20/07)

Semi-final (10/26-31)

Final Event (11/3)

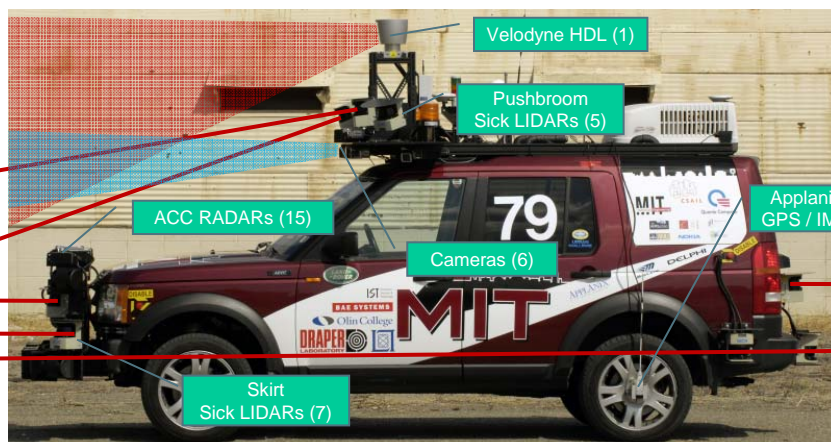


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Design Strategy

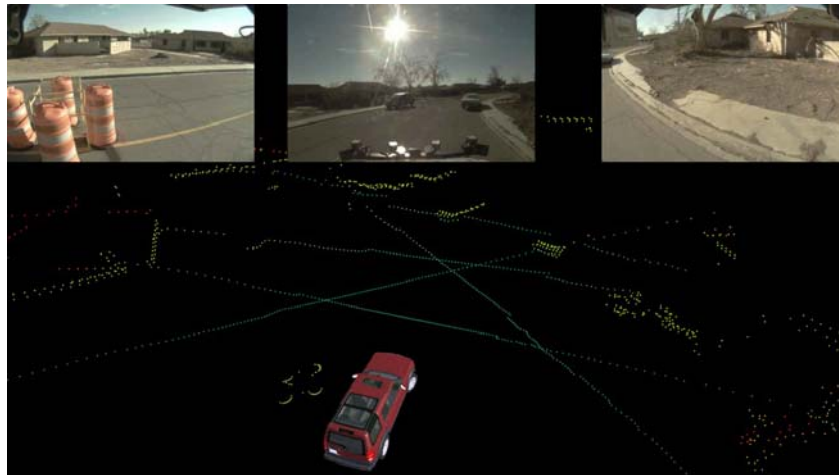
- Sensor-rich, CPU- and I/O-intensive architecture
 - Many sensors to interpret surroundings “live”
 - Intensive use of live and logged visualization
 - Many resources, to avoid premature optimization
- Redundancies:
 - Sensor type and spatial coverage
 - Closed-loop multi-level planning and control
 - Computation failover at process level
 - Firmware-mediated actuator control
- Failsafe behaviors
 - If no progress, relax perceived constraints

Our Approach



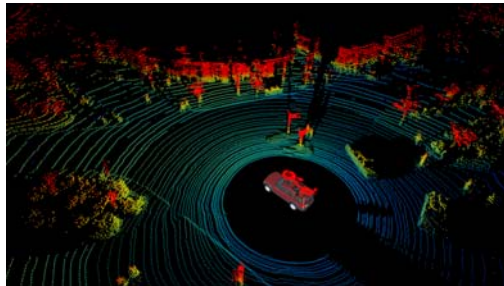
Planar Laser Range Scanners

False colored by height



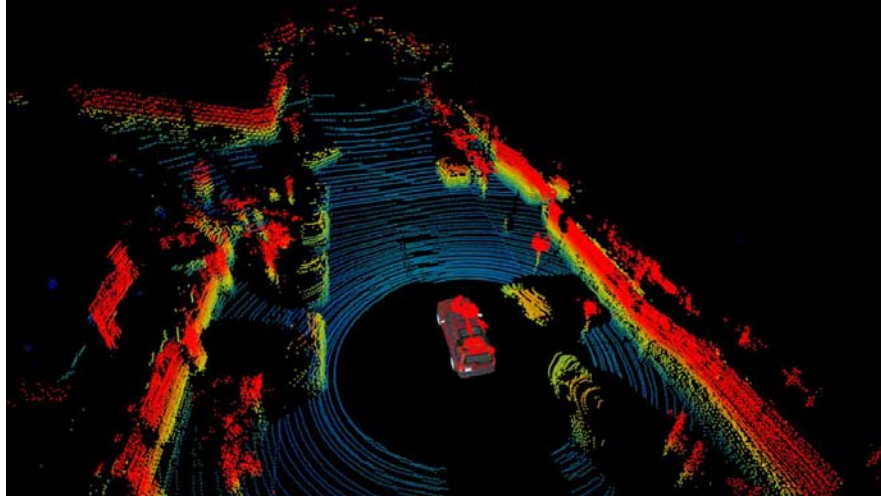
Velodyne Lidar

- 64 lasers, 360° HFOV
- Spins at 15 Hz
- Vertical FOV -24° → +2°
- Redundant (albeit relatively noisy) lidar



Sample Velodyne Data

False colored by height

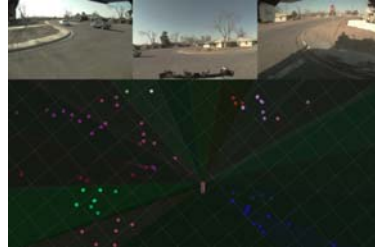


Detection of Static Obstacles



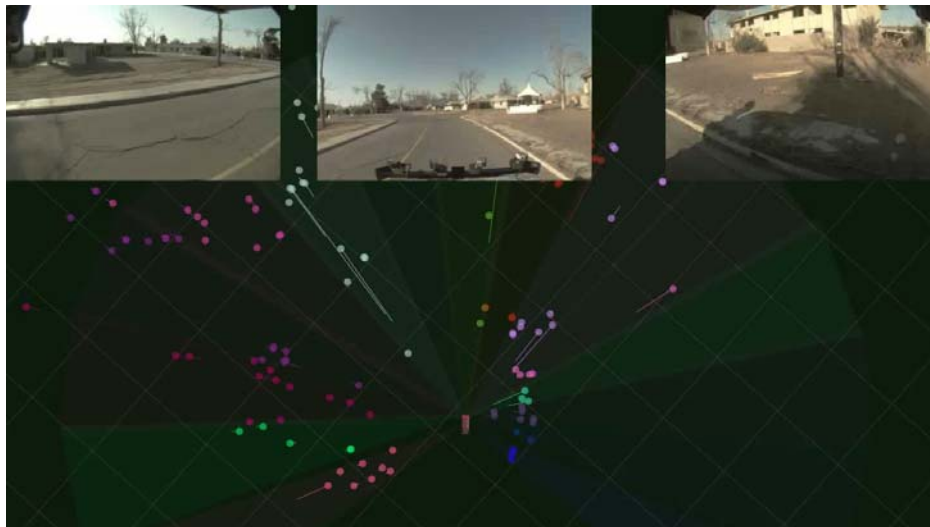
Automotive Radars

- 15 Delphi automotive radars
- Doppler range, bearing, closing speed of 20 objects @ 10Hz
- Narrow beam width
- Good far-field car detectors



Sample Radar Data

Raw range, bearing, range rate data, false-colored by radar ID



team MIT
DARPA Grand Challenge

Vehicle Detection and Tracking

CSAIL

EE
CS

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team MIT
DARPA Grand Challenge

Tracking in Cambridge

CSAIL

EE
CS

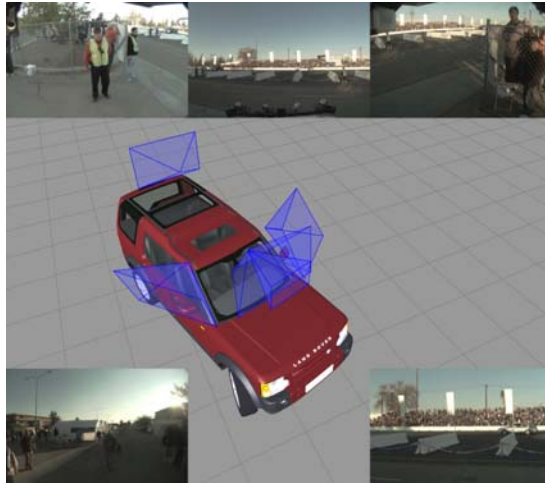
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Video Cameras

- 5 Firewire Cameras
 - Point Grey Firefly MV
- 720x480 8bpp Bayer pattern @ 22.8 fps
- ~40 MB/s (2.5 GB/min)
Lots of data!
- Purpose: Detection of painted lane markings



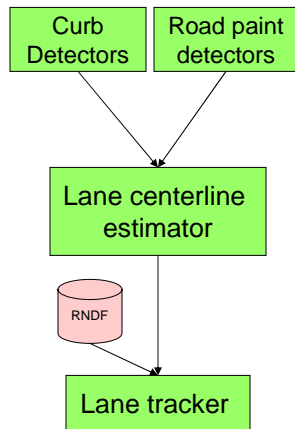
Forward left Forward center Forward right




Rear view


Narrow forward view

Lane Estimation







Closed-Loop Lane Tracking




Playback speed: 2x




One-way two-lane road
RNDF-interpolated estimate goes through trees and bushes!



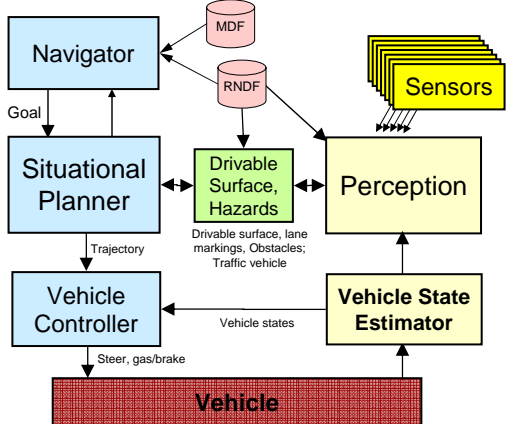
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System Architecture



- Perception
 - Vehicle surroundings
 - Vehicle location w.r.t. surroundings and RNDF
- Planning & Control
 - Codified driving rules
 - How to reach the goal



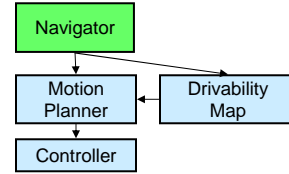
- AEVIT Vehicle Conversion (EMC) control unit
 - Continuous signal (steering, gas/brake)
 - Discrete signal (turn signals, gear shift)



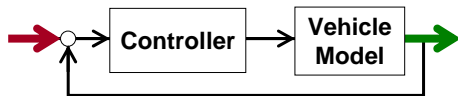
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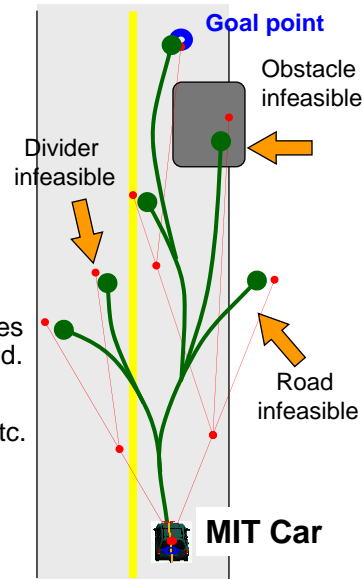
Navigator

- Mission planner
- Sets high level goals
 - “Carrot” for the motion planner
- Replan around blocked roads
- Knob on constraints in drivability map
 - Perception algorithms are not perfect
 - If car stuck and isn’t making progress, start ignoring perception (invoke failsafe levels)



Vehicle Motion Planning

- Sample the input to the **controller**

 - Dynamically feasible path
 - Closed-loop stability
- Every trajectory ends with a **stop**
 - Continuously replan, extend trajectories so that terminal segments are not used.
- Various types of hard constraints
 - Obstacle, lane markings, stop lines, etc.
 - Navigator dynamically revises constraints



Competition Vehicle: LR3

- Linux blade cluster with two fast interconnection networks
 - 10 blades each with 2.33GHz quad-core processor → 40 cores
 - Approximately 80 driving-related processes steady-state
- Many sensors
 - Applanix IMU/GPS
 - Hi-res odometry
 - 12 SICK Lidars
 - Velodyne (~64 Lidars)
 - 15 automotive radars
 - 5 video cameras
- Roof-mounted AC
- Power consumption ~5500W total
- Internal gas generator



LR3 Mobile Machine Room



Autonomous Driving Test Site

- South Weymouth Naval Air Station

- About 40 min. from MIT off 3S
- Usually \$10K/day; free to our team when no paying customer



- Large tarmac area

- Can create arbitrary (flat) road networks
- Environmentally sensitive:

- Obstacles: traffic cones
- Lane markings: only flour
- Traffic: team members' cars



NQE and Competitors





Fine-Grained Prior Map Data



- Every other team we spoke to *manually* “densified” the provided RNDF (map) data during the 48-hour pre-competition period
 - Used high-resolution geo-referenced aerial imagery
 - Added precise position and / or curvature samples at dense intervals (every few meters) along roads
- Rationales we heard for this approach:
 - “All the other teams are densifying” (not true)
 - Such “data infrastructure” will be widely available soon via commercial efforts (NavTeq, Google)
- DARPA implicitly blessed this strategy
 - 48-hour RNDF distribution; no surprise road segments



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Why This is a Bad Idea



- Prior info could be incorrect, since map data:
 - ... can be incomplete or erroneous at source
 - ... can become *stale* due to a dynamic world
 - ... can be corrupted in transmission or by bad guys
- “Locks in” reliance on precision GPS navigation
 - No matter how good, position sometimes “jumps” a few meters
 - This is an *inherent limitation* of GPS in urban environments
 - Hinders research on core problem aspect (perception)
- Brittle whole-system aspects / points of failure
 - Challenge of highly-available map data service at scale
 - Degraded or denied GPS reception
 - One team froze for 40+ minutes at starting line due to poor GPS !
- Causes human observers to misjudge cars’ abilities
 - Example DARPA webcast commentators attributed human-like driving skills to cars pulling into parking spots marked with lines



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An Alternative Direction



- Drive with just-in-time sensing, and poor-quality (or no) GPS reception
- Why?
 - Humans drove just fine before advent of precision roadmaps and GPS
 - Avoids brittle aspects of GPS-based approach
 - Technology trends (sensing, CPU, I/O, faster actuators) hold promise of achieving driving performance *superior* to that of humans
 - Social aspect: trust in sensors vs. trust in maps



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A Concrete Proposal



- Run the next Challenge **without GPS !**
- At least four good reasons to do this:
 - Bring into sharp relief which aspects of the autonomous driving problem have been solved
 - Show the military what level of capability to expect when bad guys jam their GPS reception
 - Dramatically lower the cost barrier for “garage teams” (omit ~\$75K high-end GPS/IMU systems)
 - Channel research into perception tasks rather than precision mapping and data integration



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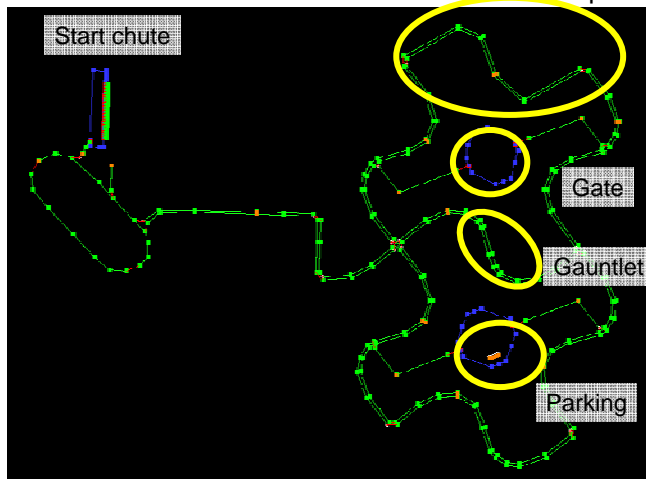
NQE and Competitors




NQE Area B


- Our very first NQE run.

Sparse Waypoints

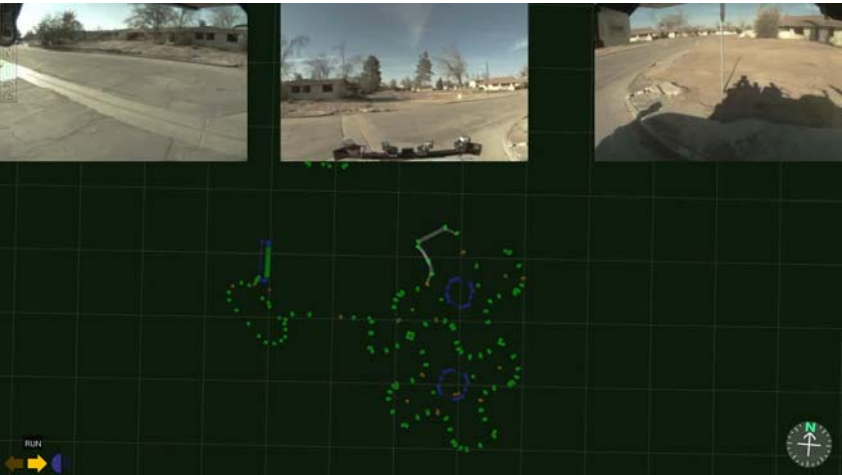





NQE Area B




Playback speed: 3.3x




One of only 2 teams to complete Area B on the first attempt.



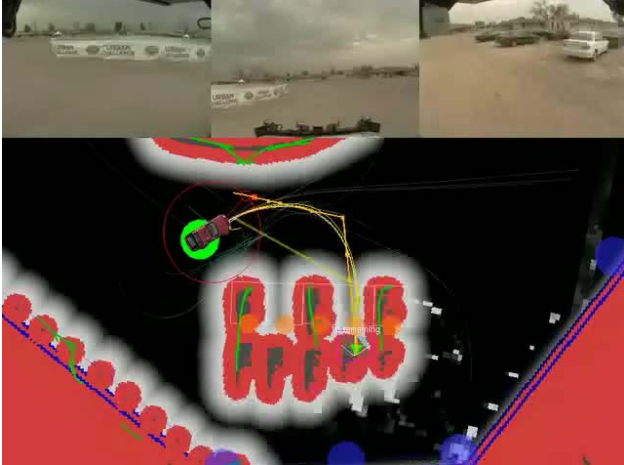
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Area B Parking Test



- Parking: RNDP target position was blocked

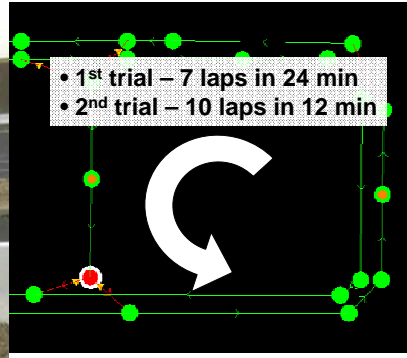




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NQE Area A

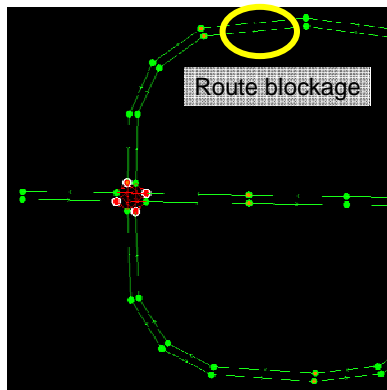
- Advanced traffic capabilities
 - Merging into traffic
 - Left turn across oncoming traffic
 - Excessive delay (> 10 sec.) prohibited
- ~10 traffic vehicles moving at 10mph.




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NQE Area C


- Objectives
 - Intersection precedence (turn-taking)
 - Blocked check points (replanning, 3-point turns)




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Urban Challenge Event (11/03/07)




- Only 11 of 35 teams selected, due to DARPA's safety concerns
- 50 human-driven traffic vehicles
- 3 MDF missions totaling ~60 miles







Urban Challenge Final Event Course Map




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Change in DARPA's Emphasis



- Focus very different from specification, NQE
 - Allowed human pre-inspection of road network
 - Opportunity to validate manually densified RNDFs
 - Simplified competition setup
 - No DARPA-generated road blockages
 - No passing or merging at speed
 - No dense human traffic or planned human challenges
 - No other vehicles (parked or moving) in parking lots
 - No GPS degradation or outages
 - RF sources turned off (plasma display, chase video)
- **Other robot cars**
 - Highly unpredictable



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Degraded Performance

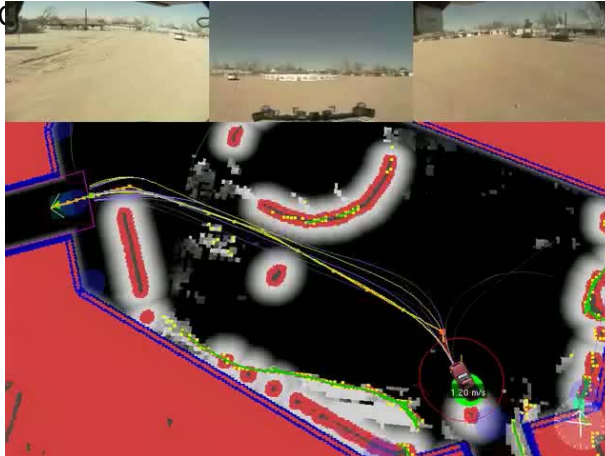
- Phantom curbs on the dirt segment
 - Had never tested on steeply-sloped dirt roads
 - Failsafe timer kicked in → disregard curbs

1817m33s, 13.76 mi @ 10.7 mph, 8 Checkpoints, 1 Failure @ Time 0:55

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Accident with CarOLO

- Accident had several contributory causes:
 - CarOLO drove into us → damaged, removed from competition
 - Hard to detect slowly moving objects, without false positives
 -



The first bot-on-bot car accident in history!

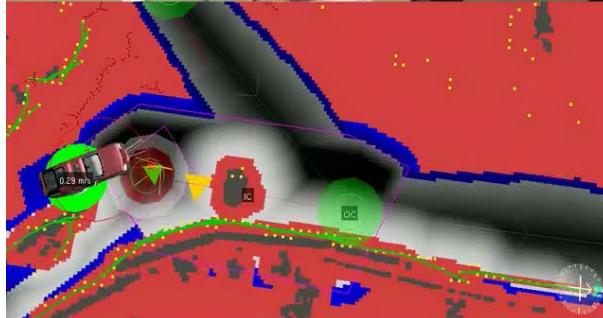
Accident with Cornell

- Cornell
 - Stopped, then reversed toward the intersection
 - Started moving as we passed
- MIT
 - Tried passing to Cornell's left
 - Returned to right lane too quickly

→ DARPA: "no fault" incident; both teams continued



The second bot-on-bot car accident in history!





Traffic Jam




- Each car waiting for another car to move
- Excess delay = 10sec → traffic jam






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High-Speed Section



- MDF speed limit: 30mph
 - Braking distance = 36m (with 2.5m/s² deceleration)
 - Standoff distance = 10m
 - Requires reliable detection range: 50m

→ Capped @25mph by our software





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Results

- 6 teams finished; 5 others removed from competition by DARPA officials
 - At-fault collisions
 - Near misses
 - Excess delay
- Many race-day firsts for us:
 - More than 20 miles in one day
 - Steep dirt (unpaved) segment
 - Mile-long, wide lanes @25mph
 - Interaction with other robots
- We drove safely
 - No processes died
 - Our chase driver: “your vehicle was always safe, in my opinion”



CMU

Stanford

Virginia Tech



Failure Modes

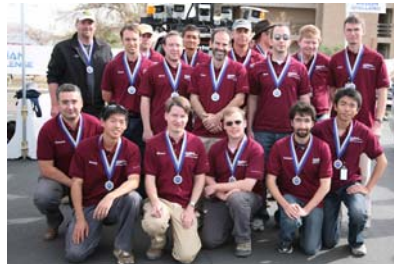
- Perception limitations
 - Hallucinated curbs (at detection size threshold)
 - Vulnerability to shadows, sun blinding
 - Sensitivity to vehicle pitch
 - Inability to track slow-moving vehicles (< 3mph)
- Control / Planning limitations
 - Occasionally failed to achieve target orientation
 - Caused over-correction, unsafe maneuvers
- Failsafe strategy
 - Unclear when to relax or observe constraints
 - Example: U-turn at roadblock, or drive around?

Teamwork!



Achievements

- Respectable rookie showing
 - First time in DGC for everyone on MIT team
- Fourth place overall
 - One of only 6 teams (of 89 initially entering) to complete UCE course
- Completed all NQE missions without manual annotation of RNDF





Lessons Learned



- About competing effectively
- About DARPA's expectations
- About the autonomous driving task
- About differing long-term approaches

More info: <http://dgc.mit.edu>



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Questions and Discussion



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