The Path to Commercial Autonomous Cars: 
*The DARPA Urban Challenge and Beyond*

Paul E. Rybski
The Robotics Institute
Carnegie Mellon University
Self-Driving (Autonomous) Cars

- No human driver required

- On-board computers use vehicle-mounted sensors to perceive the world and make driving decisions

- How close are we to this technology being ready for commercialization?

- What are the open questions and challenges?
Motivation for Autonomous Cars

• Safety[1]
  • 5.5M crashes
  • 30K deaths
  • 1.5M injuries

• Time[2]
  • Average commute time 23 minutes

• Quality of life
  • Offer greater mobility to the disabled and senior citizens

• Industrial
  • Longer hours of operation provide greater economic impact

Brief Timeline of Autonomous Cars

1937–1970s
Automated cars guided by RF or magnetic infrastructure

1980s
Bundeswehr Universität München, Germany

1995
CMU NAVLAB
“No Hands Across America”

2000–2005
CARSENSE, AHSRA Demo (Japan), CHAMELEON, DARPA Demo III, ARCOS (France), CarTalk, INVENT (Germany), PREVENT

2010
Vislab Intercont. Autonomous Challenge, Italy to China
Google cars

1965

http://www.cs.cmu.edu/afs/cs/project/alv/www/
http://www.youtube.com/watch?v=xkJVV1_4l8E
http://www.cs.cmu.edu/~red/Red/redteam.html
http://cs.stanford.edu/group/roadrunner//old/announcements.html
2007 DARPA Urban Challenge

- (Sub)Urban Autonomous Vehicle Race
- 60 miles in less than 6 hours
  - Interact with traffic
    - Intersections
    - Merging
    - Passing
    - Parking
    - Dirt Roads
  - 30 mph speed limit
- Results
  - 35 at qualifiers
  - 11 at starting line
  - 6 crossed the finish line
  - 3 finished in allowed time
The Robot Car: “Boss”

Tartan Racing is united to catalyze a technical, cultural and industrial revolution for a new class of robotics to advance the state-of-the-art in driver safety.

http://www.tartanracing.org
Challenges of Autonomous Operation

http://www.youtube.com/watch?v=EuMFD9s1oIz

Sensors on Boss

- Velodyne multi-plane lidar
  360° x 26° FOV, 60m

- Continental ISF 172 lidar
  14°, 150m

- IBEO
  180° FOV, multi-plane, multi-echo

- Continental ARS 300 radar
  60/17°, 60/200m

- Applanix GPS/INS
  90/180° FOV, 40m

- SICK Scanning Lidar
  90/180° FOV, 40m

Object Tracking

~16 Sensors total
Autonomous Perception: Detecting and Tracking Moving Objects

Autonomous Perception:
Obstacle Detection & Road Following

Boss Perception System in Action

http://www.youtube.com/watch?v=njwx7jskDPO
Mission and Path Planning


Current Challenges for Autonomous Car Research

• Challenges not found in the 2007 race:
  • Traffic lights
  • Traffic signs
  • Pedestrians
  • Bikes
  • Speeds > 30mph
  • Coordinated driving
  • Cross-country driving
  • Construction zones
  • Humans directing traffic

• Lessons learned from the Urban Challenge:
  • Driving is a social activity
    • Subtle communication of intent occurs between drivers
  • Perception is very hard
    • Real-time challenges (e.g. CPU limits and bandwidth)
    • The “right” sensor doesn’t yet exist for urban driving
    • Contextual information must be used to fit ambiguous sensor data to known models
    • Advanced representations for the world are required
Industrial Constraints Towards Commercialization

- Commercial LIDAR sensors are generally expensive
  - Few systems have a clear path to production in terms of automobile deployment
- RADAR is an option on higher-end vehicles
  - Adaptive cruise control
- Cameras are already considered future car accessories
  - Backup cameras are on some vehicles now
- Computers are getting faster
  - Computational requirements for safe operation are still significant

Ray Resendes, “IntelliDrive Vehicle Communications For Safety”, US Department of Transportation
National Highway Traffic Safety Administration
Keynote Address for 2010 IEEE Intelligent Vehicles Symposium
http://www.youtube.com/watch?v=9Q1HyTvw304
Detecting and Tracking Vulnerable Road Users

- Autonomous vehicles must be aware of and navigate around cars as well as vulnerable road users:
  - Bicycles
  - Pedestrians
  - Motorcycles

- Bicyclists must share urban road lanes with cars and move at comparable speeds

- Bicyclists are particularly unprotected against injury in a collision (e.g. no crumple zone)

- In 2009, 630 bicyclists were killed and 51,000 were injured in traffic accidents in the United States.[1]

Vision-Based Detection and Tracking of Moving Objects

Detecting Moving Objects


DPM HOG Algorithm

Visual Bicycle Detection and Tracking from a Moving Vehicle

Hyunggi Cho and Paul E. Rybski

http://www.ri.cmu.edu/research_project_detail.html?project_id=653

http://www.youtube.com/watch?v=oVfKS_qH068
Google’s Autonomous Cars

Autonomous Driving
Google’s modified Toyota Prius uses an array of sensors to navigate public roads without a human driver. Other components, not shown, include a GPS receiver and an inertial motion sensor.

LIDAR
A rotating sensor on the roof scans more than 200 feet in all directions to generate a precise three-dimensional map of the car’s surroundings.

POSITION ESTIMATOR
A sensor mounted on the left rear wheel measures small movements made by the car and helps to accurately locate its position on the map.

VIDEO CAMERA
A camera mounted near the rear-view mirror detects traffic lights and helps the car’s onboard computers recognize moving obstacles like pedestrians and bicyclists.

RADAR
Four standard automotive radar sensors, three in front and one in the rear, help determine the positions of distant objects.

Source: Google


http://www.youtube.com/watch?v=oMdcWHnbhw


http://www.youtube.com/watch?v=YaGJ6nH36uI
The Future: Challenges and Directions

- Perception
  - The world is a vast and complicated place
  - Assumptions and *a priori* models will only get you so far
  - Sensor technology needs to evolve some more

- Vehicle control
  - Making intelligent decisions when uncertain about the state of the world
  - Experience is the best teacher: can cars learn from that?

- Human and car collaboration
  - Some people will still want to drive cars. How best can the controls be shared?
  - How can we exploit vehicle-to-vehicle and vehicle-to-infrastructure?
Thank you!