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

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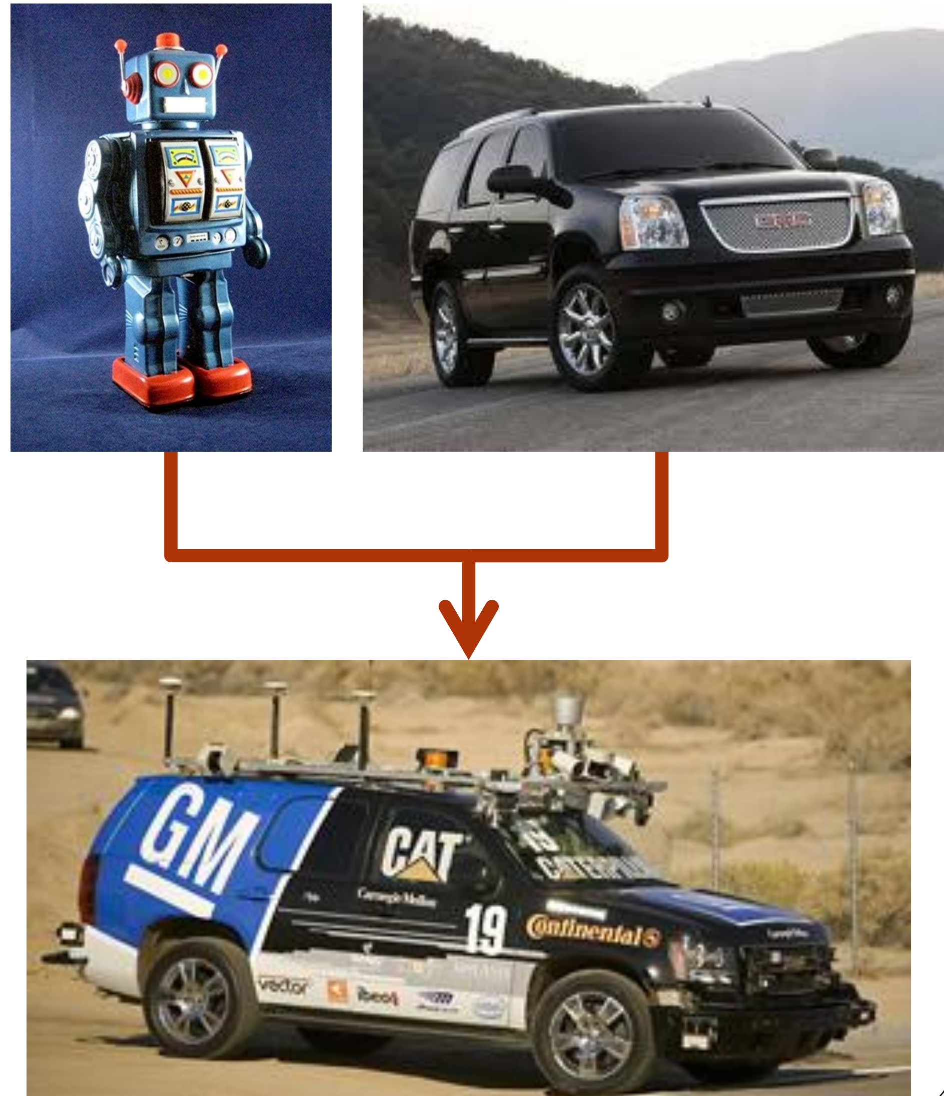
Self-Driving (Autonomous) Cars

- **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

[1]US Department of Transportation, http://www-nrd.nhtsa.dot.gov/Pubs/811363.PDF, (2009)

[2] http://www.gallup.com/poll/142142/Wellbeing-Lower-Among-Workers-Long-Commutes.aspx , (2010)

Brief Timeline of Autonomous Cars

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1937 – 1970s	1980s	1995	2000-2005	2010
Automated cars guided by RF or magnetic infrastructure	Bundeswehr Universität München, Germany	CMU NAVLAB "No Hands Across America"	CARSENSE, AHSRA Demo (Japan), CHAMELEON, DARPA Demo III, ARCOS (France), CarTalk, INVENT (Germany),PREVENT	Vislab Intercont. Autonomous Challenge, Italy to China Google cars

1965 — 1970 — 1975 — 1980 — 1985 — 1990 — 1995 — 2000 — 2005 — 2010

1977	1987-1995	1997	2004, 2006	2007
Tsukuba Mechanical Engineering laboratory, Japan	EUREKA Prometheus Project, Pan-European	AHS Demo, San Diego, CA, USA	DARPA Grand Challenges, USA	DARPA Urban Challenge, USA

NAVLAB No Hands Across America (2005) : Highway driving

http://www.cs.cmu.edu/afs/cs/project/alv/www/

http://www.youtube.com/watch?v=xkJVV1_4l8E

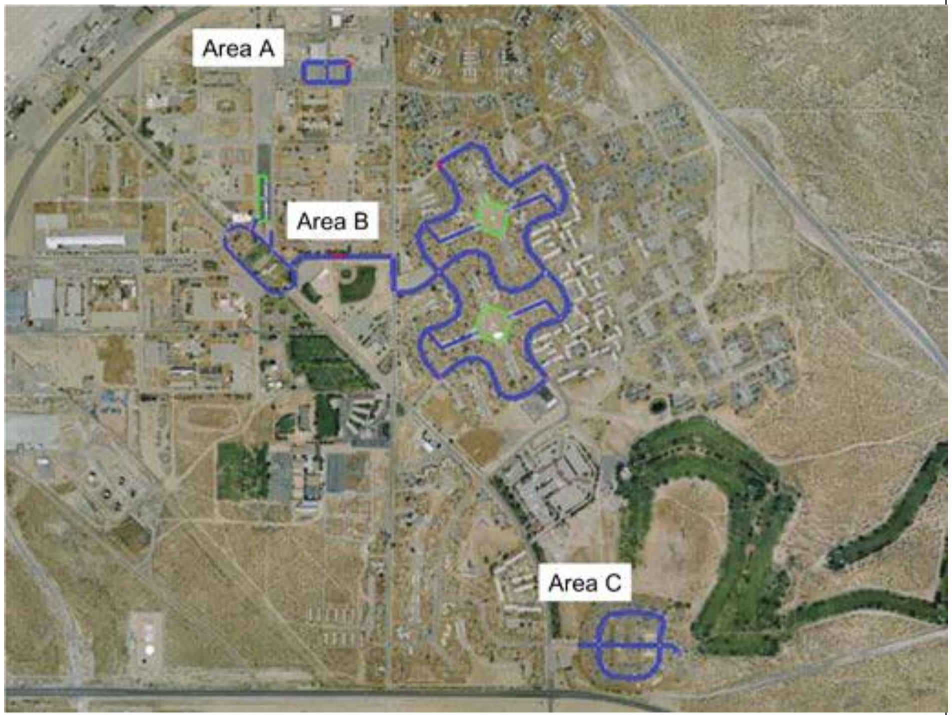
DARPA Grand Challenge (2004, 2006): High-speed offroad driving

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”

http://www.tartanracing.org

Challenges of Autonomous Operation

http://www.youtube.com/watch?v=EuMFD9s1oIs

Urmson, C., et al, "Autonomous driving in urban environments: Boss and the Urban Challenge," Journal of Field Robotics Special Issue on the 2007 DARPA Urban Challenge, Part I, Vol. 25, No. 8, June, 2008, pp. 425-466

Sensors on Boss

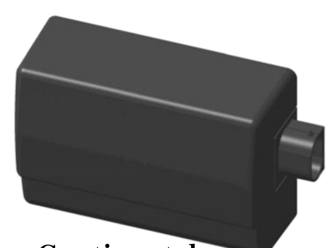
Velodyne
multi-plane lidar
360°x26° FOV, 60m

Applanix
GPS/INS

SICK Scanning Lidar
90/180° FOV, 40m

Continental
ISF 172 lidar
14°, 150m

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

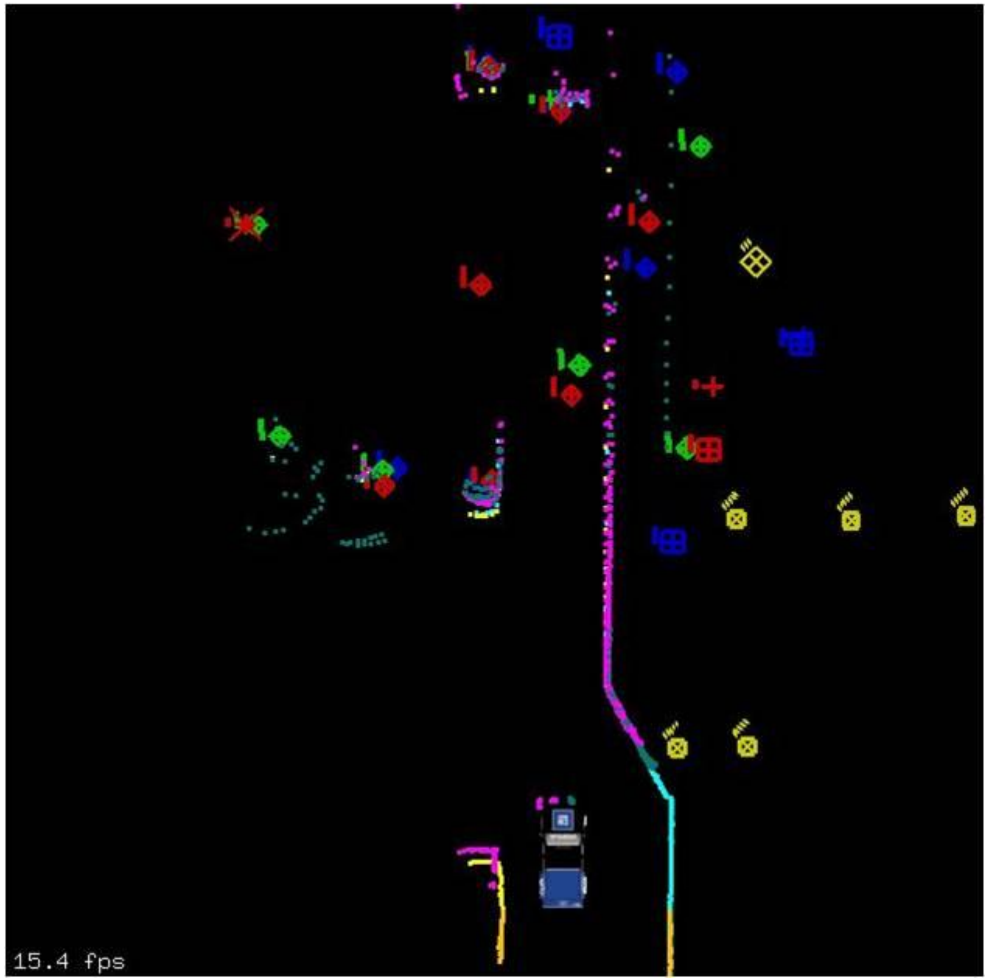


Continental
ARS 300 radar
60/17°, 60/200m

~16 Sensors total

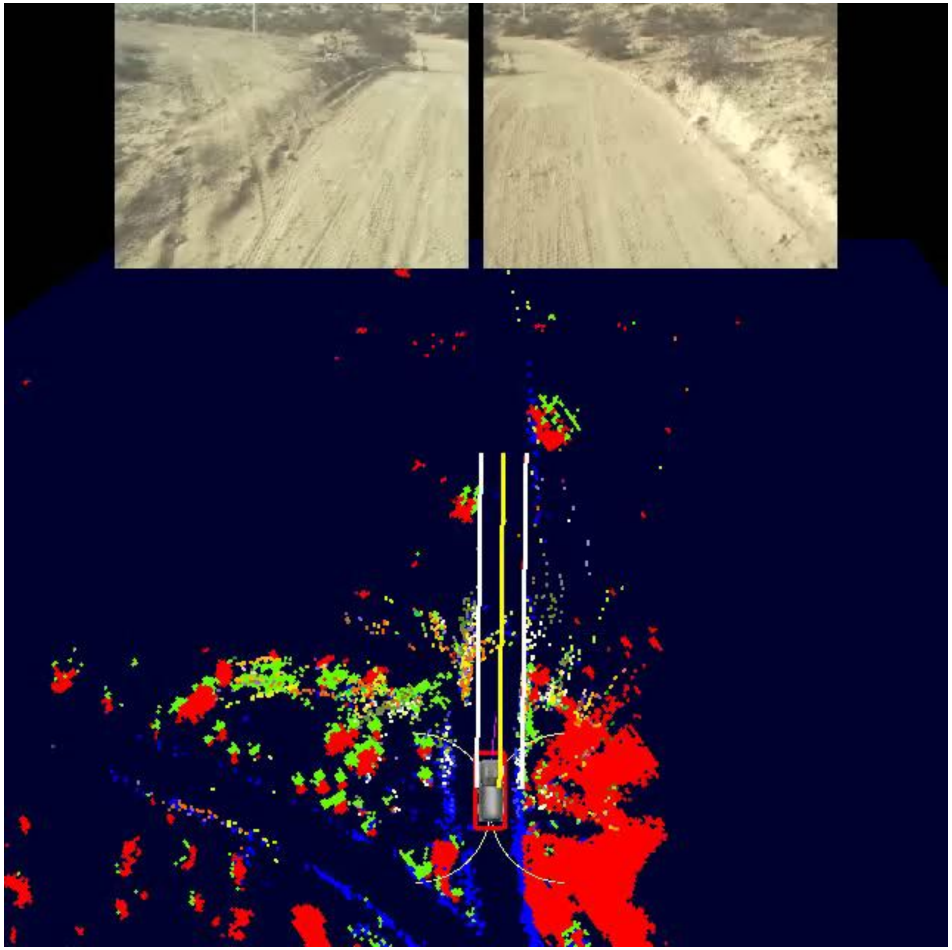
Object Tracking

Autonomous Perception : Detecting and Tracking Moving Objects



M. Darms, P. E. Rybski, C. Baker, C. Urmson, "Obstacle Detection and Tracking for the Urban Challenge," in IEEE Transactions on Intelligent Transportation Systems, 10(3), pp 475-485, Sept, 2009.

Autonomous Perception : Obstacle Detection & Road Following



K. Peterson, J. Ziglar, and P. E. Rybski, "Fast Feature Detection and Stochastic Parameter Estimation of Road Shape using Multiple LIDAR," in proceedings of the IEEE/RSJ 2008 International Conference on Intelligent Robots and Systems, September, 2008.

Boss Perception System in Action

http://www.youtube.com/watch?v=njwx7jskDPo

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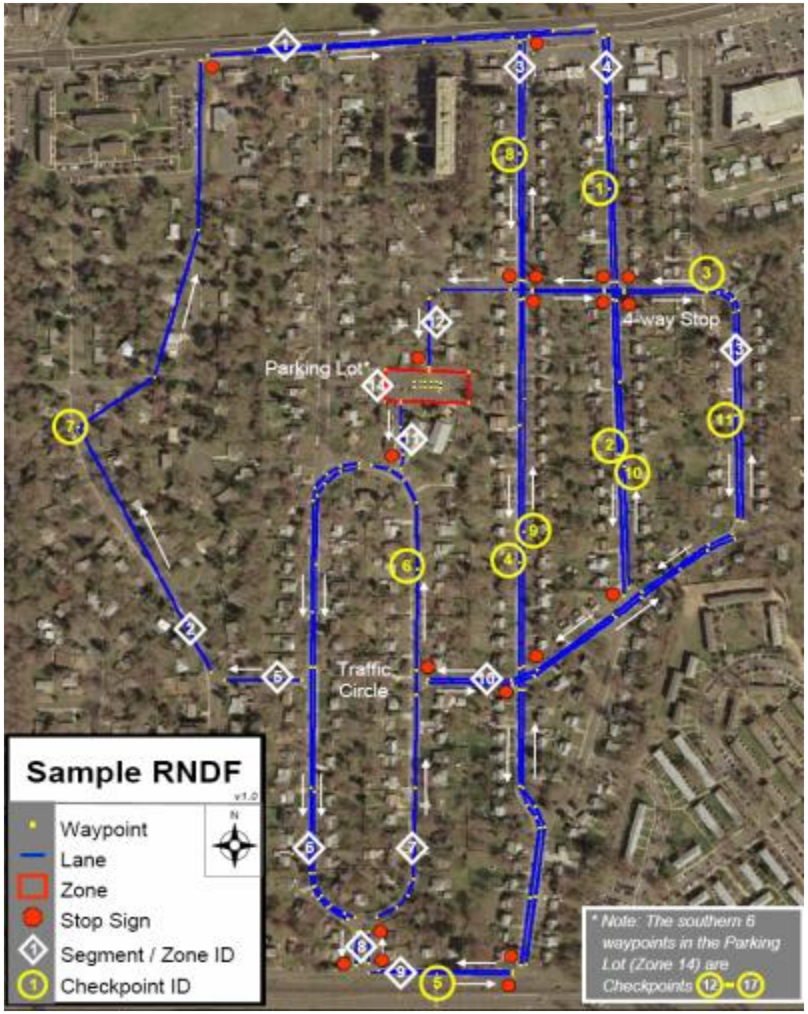
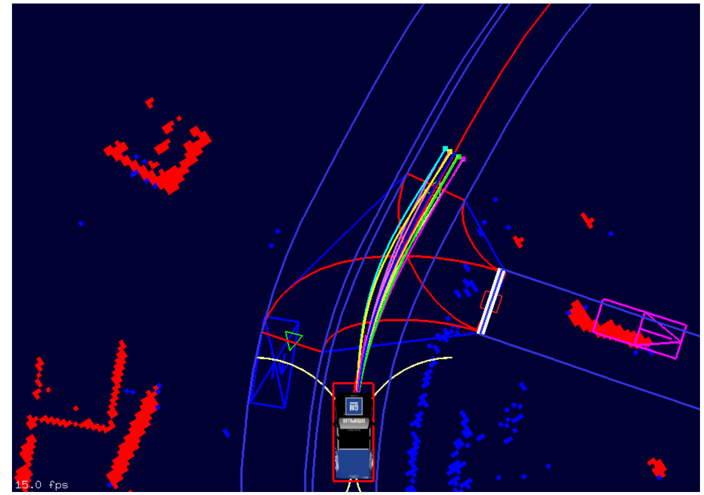
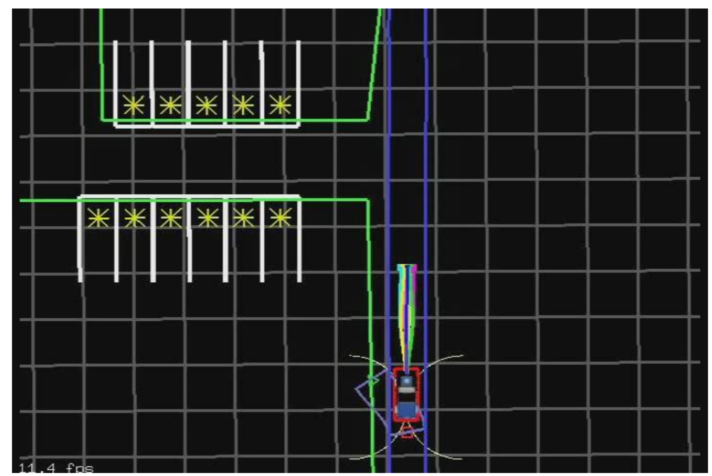
Mission and Path Planning



D. Ferguson, C.Baker, M. Likhachev, and J. Dolan, "A Reasoning Framework for Autonomous Urban Driving," *Proceedings of the IEEE Intelligent Vehicles Symposium (IV 2008)*, June, 2008, pp. 775-780.





C. Baker, D. Ferguson, and J. M. Dolan, "Robust Mission Execution for Autonomous Urban Driving," *10th International Conference on Intelligent Autonomous Systems (IAS 2008)*, July, 2008, pp. 155-163.

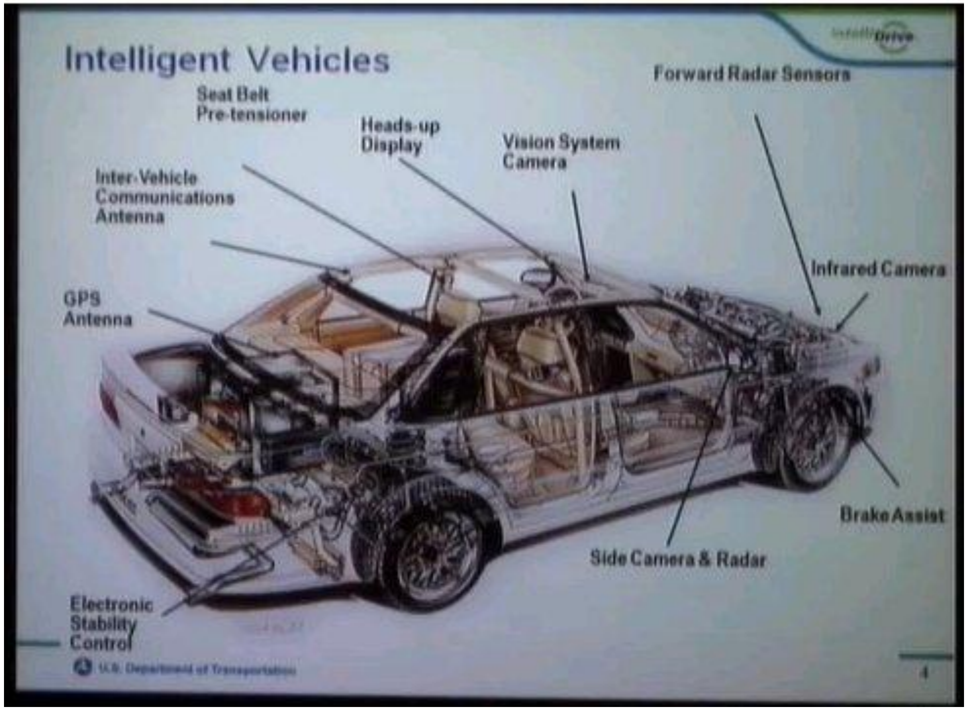
Current Challenges for Autonomous Car Research

- 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 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=9Q1fytVw304

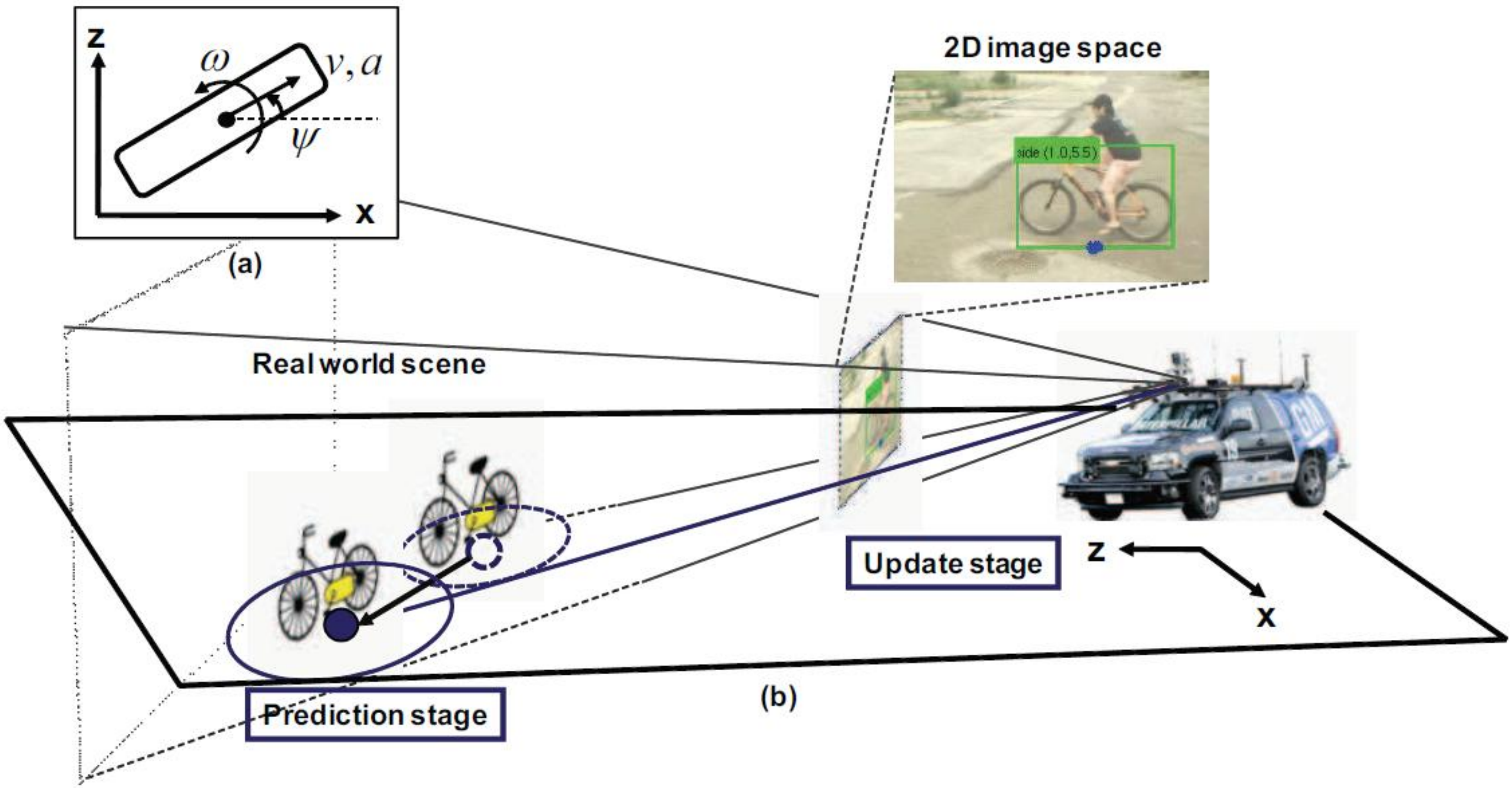
Detecting and Tracking Vulnerable Road Users

- 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]

http://www.youtube.com/watch?v=Dab48_0rYEU

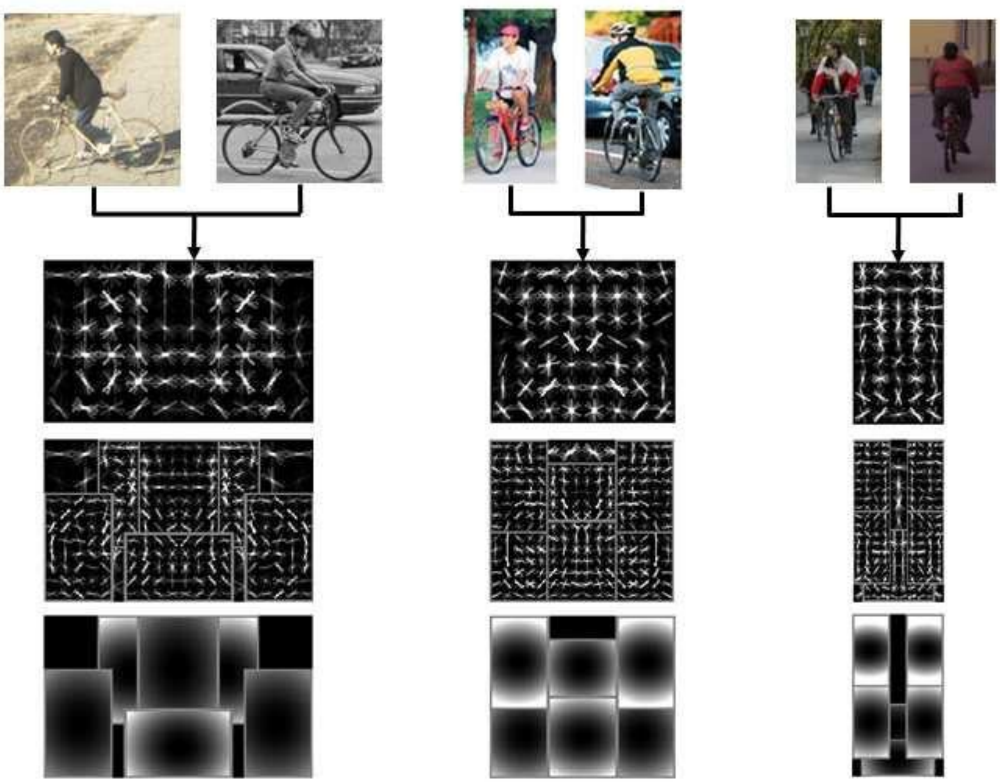
[1] http://www-nrd.nhtsa.dot.gov/Pubs/811386.pdf

Vision-Based Detection and Tracking of Moving Objects



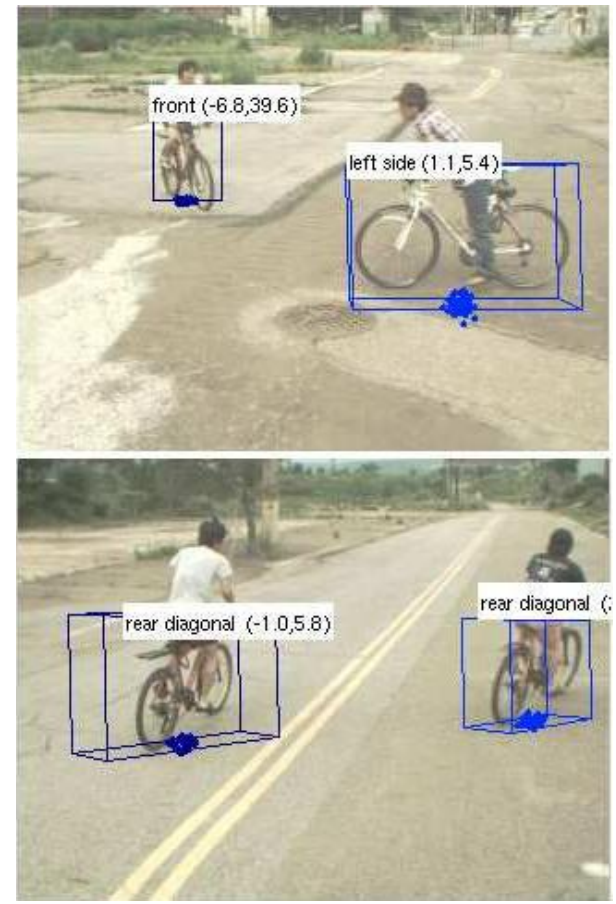
H. Cho, P. E. Rybski, W. Zhang, "Vision-based 3D Bicycle Tracking using Deformable Part Model and Interacting Multiple Model Filter," *in proceedings of the IEEE2011 International Conference on Robots and Automation, May, 2011.*

Detecting Moving Objects



DPM HOG Algorithm

P. F. Felzenszwalb, R. B. Girshick, D. McAllester, and D. Ramanan. Object detection with discriminatively trained part based models. IEEE Transactions on Pattern Analysis and Machine Intelligence, 99, 2009.

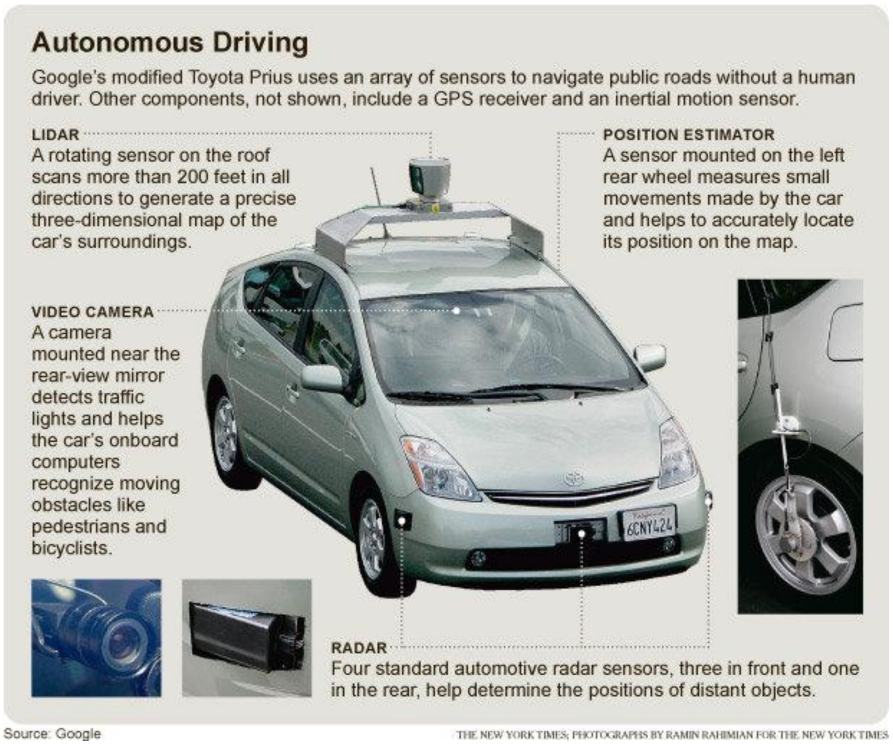


H. Cho, P. E. Rybski, W. Zhang, "Vision-based 3D Bicycle Tracking using Deformable Part Model and Interacting Multiple Model Filter," *in proceedings of the IEEE2011 International Conference on Robots and Automation, May, 2011.*

Visual Bicycle Detection and Tracking from a Moving Vehicle

http://www.youtube.com/watch?v=oVfKS_qH068

Google's Autonomous Cars



http://www.nytimes.com/imagepages/2010/10/10/science/10googleGrfxA.html?ref=science

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

http://www.youtube.com/watch?v=YaGJ6nH36uI

John Markoff, "Smarter than you Think : Google Cars Drive Themselves, in Traffic, " New York Times, October 9, 2010
http://www.nytimes.com/2010/10/10/science/10google.html

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!