Autonomous Driving in Urban Environments: Boss and the Urban Challenge

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Introduction

- Defense Advance Research Project Agency (DARPA) announced grand challenge on Autonomous Vehicle. In 2007 Urban Challenge Boss won the competition.
- **Topics :**
- Introduction to “Boss”
- Components, Algorithms and Mechanisms :
  - High level view on components : Example
  - Boundaries, challenges, and outcome
  - Results
- Conclusion and Comments

Boss

- **Sensors :**
  - 17 different Radar and Lidar and
  - Global positioning system [GPS].
- **Computation :**
  - Compact PCI chassis with **ten** 2.16 gigahertz Core2Duo processors,
  - each with 2 gigabytes of memory and a pair of gigabit Ethernet ports
- **Power :**
  - Stock 12 V with upgraded alternator and
  - Auxiliary 24V DC power equipped with an alternator giving output of AC 120V

Boss Subsystems/1

- **The motion planning subsystem**
  - Structured driving (Road following)
  - Unstructured driving (manoeuvring in parking lots)

- **The perception subsystem** :
  - Provides composite model of the world
  - a static obstacle map
  - a list of moving vehicles
  - Location of Boss relative to the world.

Boss Subsystems/2

- **The mission planner :**
  - Computes all possible routes from current position to next destination
  - Keeping in knowledge about road blockage, legal speed limit etc.

- **The behavioural system**:
  - Formulates problem definition for the motion planner.
  - Makes decision to execute the mission plan. Handles error recovery as well.

- **Software Subsystem** :
  - implementation of algorithms,
  - online/off line data log
  - visualization utilities

Motion Planning/1

- **Trajectory Generation** , **On road navigation**, and **Zone navigation**
- Generates a **set** of candidate trajectories depending on the evaluation function.
- Evaluation function is dependent on ***static and dynamic obstacles***, ***curbs***, ***speed*** , ***curvature*** and ***deviation from the path***.

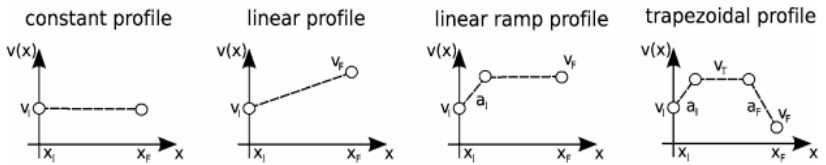

Figure 3. Velocity profiles used by the trajectory generator.

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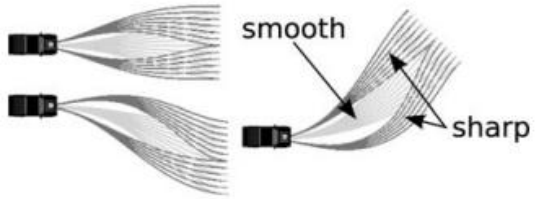
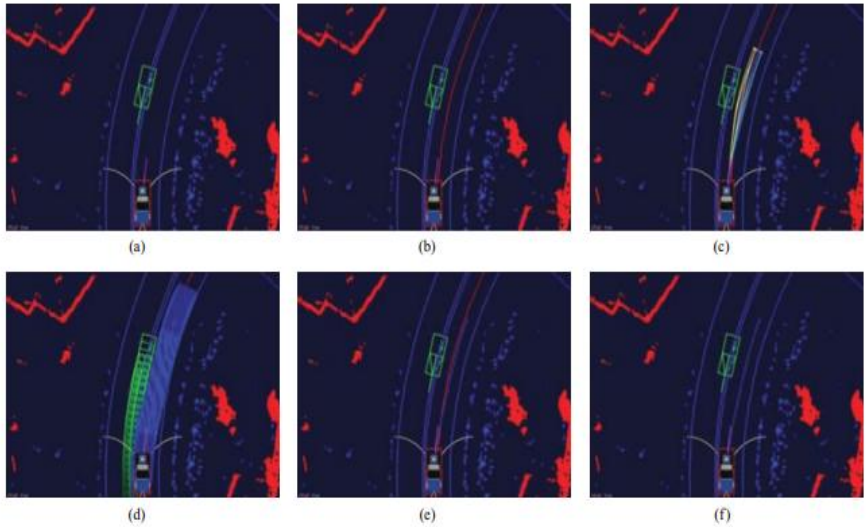


Figure 4. Smooth and sharp trajectories. The trajectory sets are generated to the same endpoints but differ in their initial commanded curvature.

Motion Planning/2

- Example of evaluation :
  - Depending on the proximity of :
    static and dynamic obstacles
  - Distance from the center path line,
    smoothness etc.
  - One is executed

- Zone Navigation : Why ?
  - Executing : Parking / Exit / Intersection
  - Reverse calculation from destination.



Perception/1

- **The perception subsystem** : Provides composite model of the world.
- Moving Obstacle Detection and Tracking
  - Classification of movement state
  - Generates a list of object hypothesis that are accompanied with movement states.
  - Example

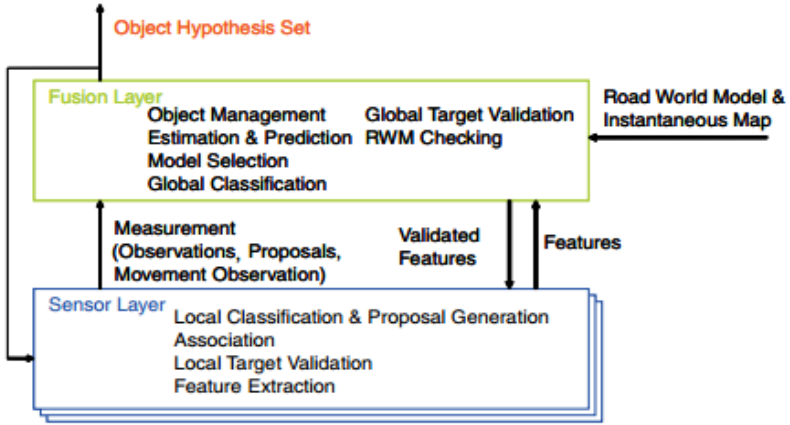


Figure 8. The moving obstacle detection and tracking system architecture.

Perception/2

- Static Obstacle Detection and Mapping (two algorithms)
  - Road – exploits prior knowledge of the road but also takes geometric cues.
  - Geometric features (curbs, berms, and bushes)
- Roadmap localization:
  - For known paved road
- Road Shape estimator
  - For unknown and unpaved road

Mission Planning

- **The mission planner :**
  - Computes all possible routes from current position to next destination.
  - Detecting Blockage
  - To determine whether there is a blockage
    - Boss can directly detect the blockage or
    - Assume it by a failure to navigate a lane

- After detecting Blockages :
- [*Particularly difficult cases include planning to a goal immediately on the other side of a newly discovered blockage and Behaving reasonably when a one-way street becomes blocked. Both resulting revisiting of blockage and consuming time*] [1]

- Each time a change is observed, the mission planner regenerates a new policy.

Behavioral Reasoning

- **Executing the policy on :**
- Making lane-change, precedence, and safety decisions, recovering from anomalous situations.
- Recovering from anomalous situations
- **Components :**
- **Intersections and Yielding**
  Precedence Estimation ,Gridlock Management
- **Distance Keeping and Merge Planning**
- **Error Recovery**
  On-Road, Intersection, Zone Failures
- **Example :** Merging into a lane (goal)

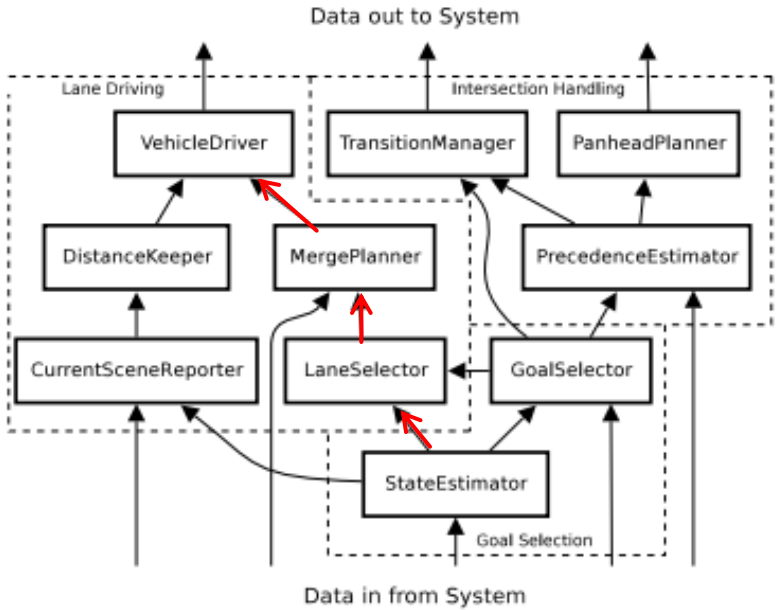


Figure 14. High-level behaviors architecture.

Software Structure

Communication Library	Interfaces Library	Configuration Library	Task Library
Unix Domain Sockets TCP/IP and UDP, interchangeability of components, anonymous publish/subscribe options	Dynamiccally loads interfaces at runtime Supports interfaces to be built on top of interfaces to form composite models	Supports task to add parameters specific to its operation.	Provides event loop and establishes communication with other tasks as per request

Debug Logger	Log Playback
Send debug messages to components of the system	Provides a way of logging any interface is the system

Tartan Racing Operator Control Station (TROCS)
A GUI providing operator, engineer, or tester way to interact with the vehicle. Used to start and stop the software, debugging, viewing stats health etc. Custom widgets for special monitoring can also be provided by this.

Testing

- **Two Vehicles** on test
- **Three states:**
  - -> Debug -> Test -> Evaluate the system
- Total 16 months of developing = 3000 Miles
- Independent Regressive system testing for Periodic enduring test

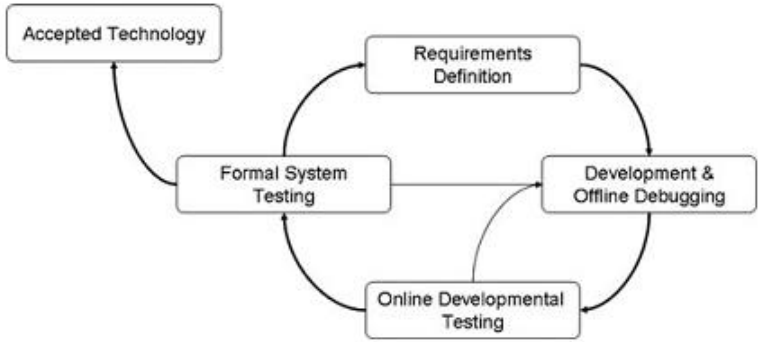


Figure 24. The requirements and testing process used in the development of Boss.

- Interesting finding:
  - Electronic shorting problem that was result of a 2mm gash in signal line bus causing total power loss.

Performance at NQE & Final

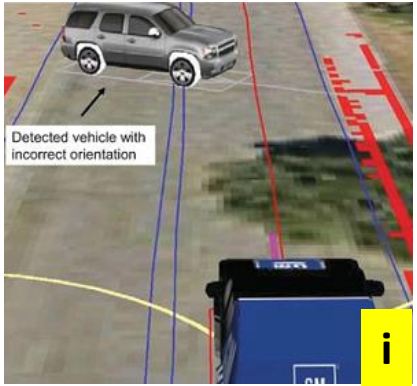
Zone A	Zone B	Zone C
Merge and move into dense moving traffic	Long road through neighborhood	Short course
↓	↓	↓
Asses gaps between moving vehicle with safety and no delay.	Avoid park cars, construction areas, and other road blocks	Handle four way intersection, rerouting around unexpected road block

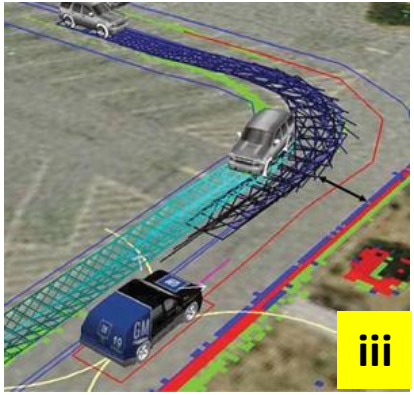
- Boss completed in **4h10m20s** - 19 min faster the the second place holder Junior (Stanford University)

- With speed of 22.5 km/h (simulated 26.2km) bounded by speed limits.

Significant Incidents

- Zone C: U Turn confusion : going into the Curb
- Predict dust cloud to be obstacle. [ii]
  - Obstacle detection algorithm was modified to treat include obstacles in blind spot
- Zone B: BUG created location error of 30m
  - Causing to back up when faced with parked cars (insufficiency of the road) ;
  - DARPA had to pause Boss
- Zone A : U Turn maneuver caused by not updating the List of moving objects [iii]





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Lesson Learned and Limitation

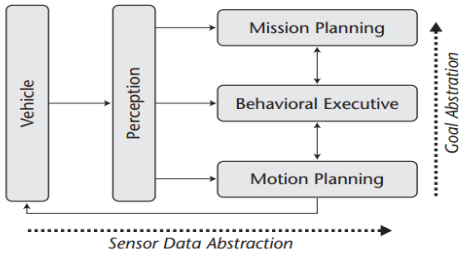
- Off-the-shelf hardware is insufficient.
- Road shape estimation needs to be changed for robust usage in all roads.
- Rich element detection ; disguise between vehicle and other entity (barrel)
- Lacks and persists issues with validation and verification of world model building.
- Recovered complex situation but took considerable time to do so.

Conclusion and Comments

- **Resulted in** : Development of behavior engine, Obstacle detection-tracking , Road Navigation, Testing methodology.

- **Comments/Critique :**
  - Strength : Very detail.
  - Real world detection improvement? -Refining object hypothesis. Eg : Human/Animal
  - Defining emergency protocol ?
  - Perception : **Statistical model** of dynamic object ?
  - Improve on Software architecture overview.
  - Possibility of communication with other vehicles to get subtle cues.

[2]



References

- 1. **Autonomous Driving in Urban Environments: Boss and the Urban Challenge** by Chris Urmson, Joshua Anhalt, Drew Bagnell, Christopher Baker, Robert Bittner,Tugrul Galatali, Chris Geyer,Michele Gittleman, Sam Harbaugh,Martial Hebert, Thomas M. Howard,Sascha Kolski, Alonzo Kelly,Maxim Likhachev, Matt McNaughton,Nick Miller,Kevin Peterson, Brian Pilnick,Raj Rajkumar, Paul Rybski, Bryan Salesky,Young-Woo Seo, Sanjiv Singh, Jarrod Snider,Anthony Stentz, William “Red” Whittaker,Ziv Wolkowicki, Jason Ziglar Hong Bae, Thomas Brown, Daniel Demitrish,Bakhtiar Litkouhi, Jim ickolaou,Varsha Sadekar, Wende Zhang Joshua Struble and Michael,Taylor Michael Darms, and Dave Ferguson.

- 2. **Autonomous Driving in Traffic: Boss and the Urban Challenge** by Chris Urmson, Chris Baker, John Dolan, Paul Rybski, Bryan Salesky, William “Red” Whittaker, Dave Ferguson, and Michael Darms