Legs, Hands, and Wheels:
Bridging the Gap Between High-Level Planning and Low-Level Control

James Kuffner

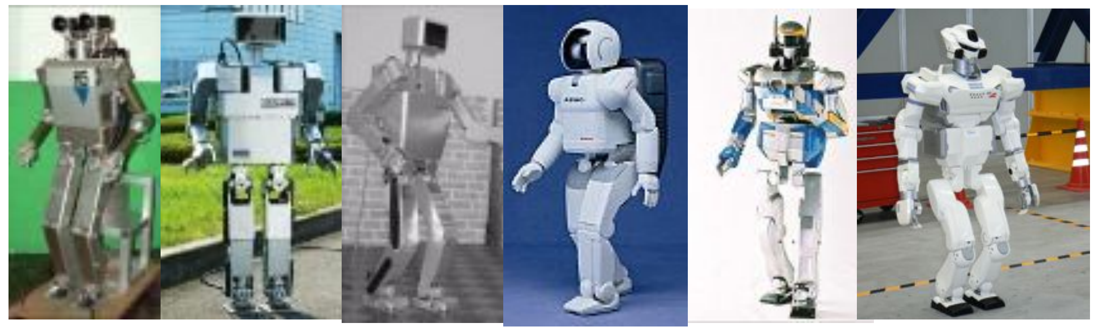
The Robotics Institute
Carnegie Mellon University

(currently full-time research at Google)

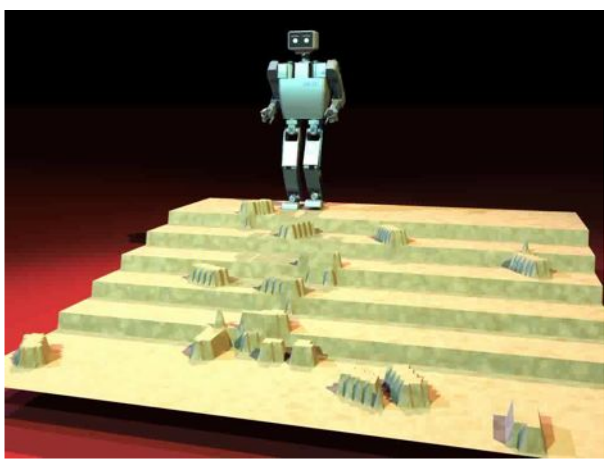
Digital Human Research Center (AIST)

Humanoid Motion Planning (1995-2011)

- Stanford University
  1995-1999
- University of Tokyo
  JSK Lab
  1999-2001
- Carnegie Mellon University
  The Robotics Institute
  2001-*present*
- Digital Human Research Center (AIST)
  2001-*present*



H5 **H6** **H7** **Asimo** **HRP2** **HRP3**



Self-driving Cars

Google™

The New York Times

Science

WORLD | U.S. | N.Y. / REGION | BUSINESS | TECHNOLOGY | SCIENCE | HEALTH | SPORTS | OPINION

SMARTER THAN YOU THINK

Google Cars Drive Themselves, in Traffic

Ramin Rahimian for The New York Times

Dmitri Dolgov, a Google engineer, in a self-driving car parked in Silicon Valley after a road test.

By JOHN MARKOFF
Published: October 9, 2010

MOUNTAIN VIEW, Calif. — Anyone driving the twists of Highway 1 between San Francisco and Los Angeles recently may have glimpsed a Toyota Prius with a curious funnel-like cylinder on the roof. Harder to notice was that the person at the wheel was not actually driving.

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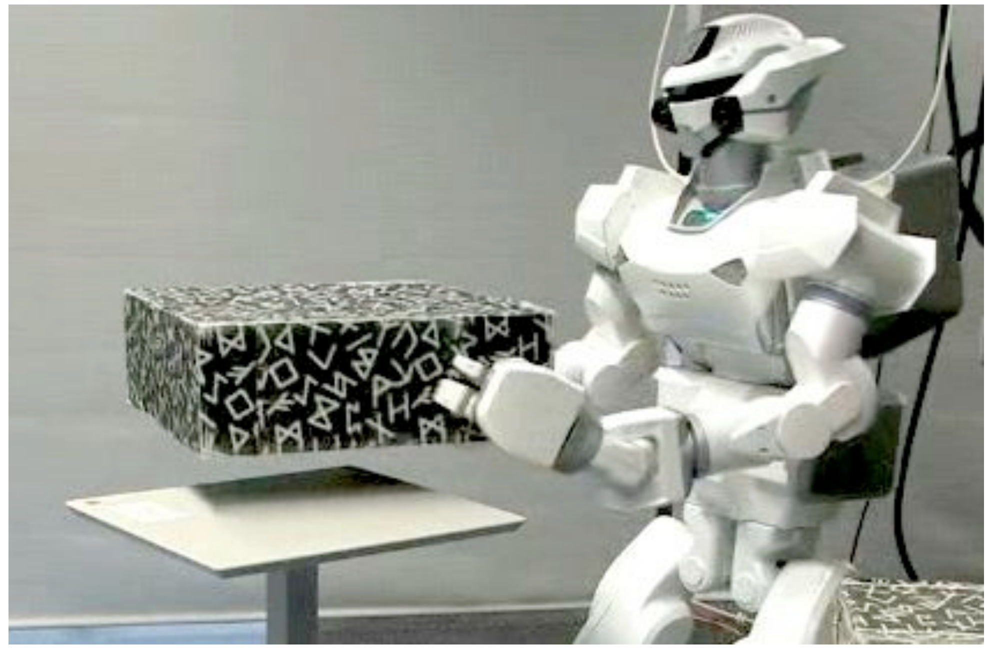
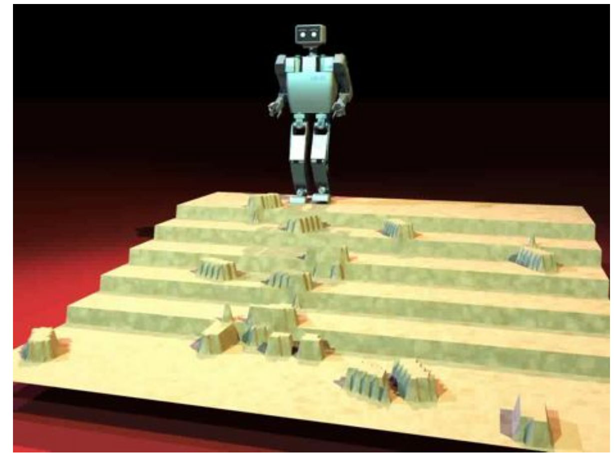
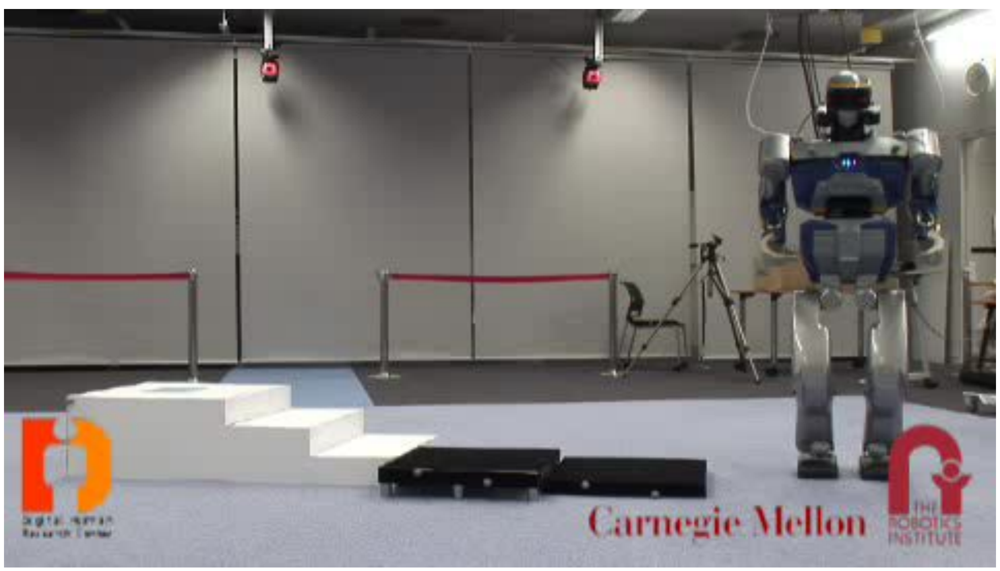
Challenges for Motion Planning in the "Real World"

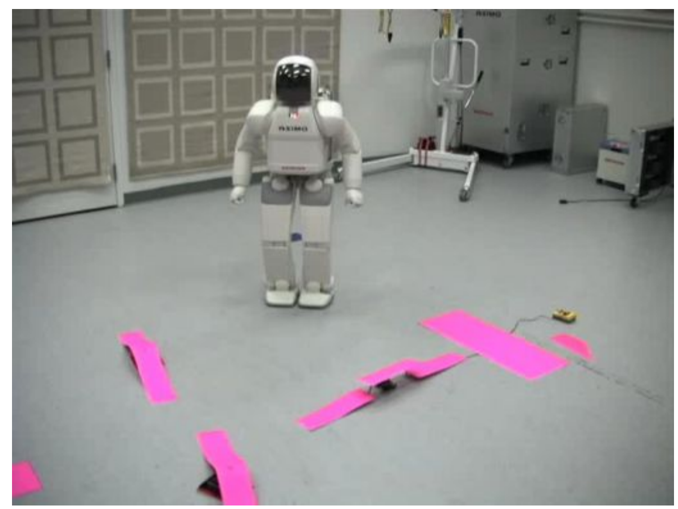


- Uncertainty
  - Prior models
  - Perception
  - Control
- Search Space
  - Continuous
  - High-dimensional
- Hard, real-time constraints

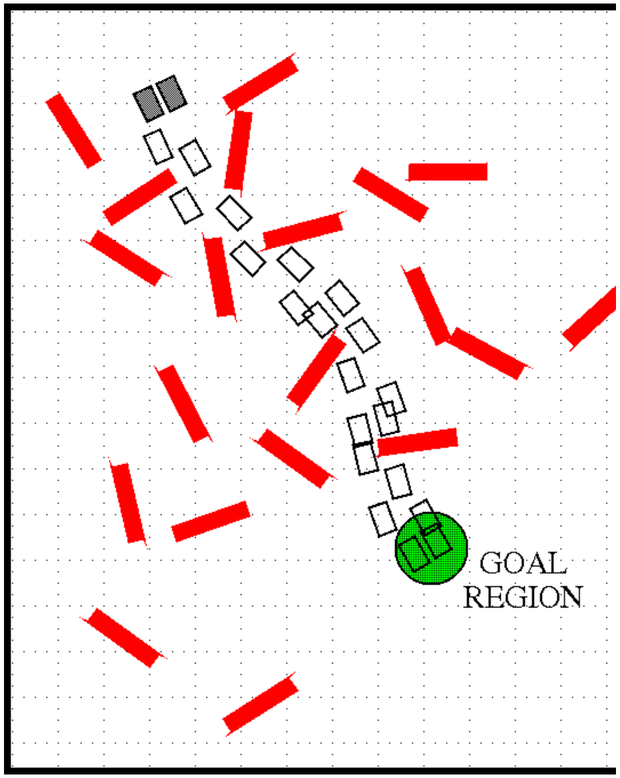
Autonomous Humanoid Navigation: "Footstep Planning" (2000-2010)



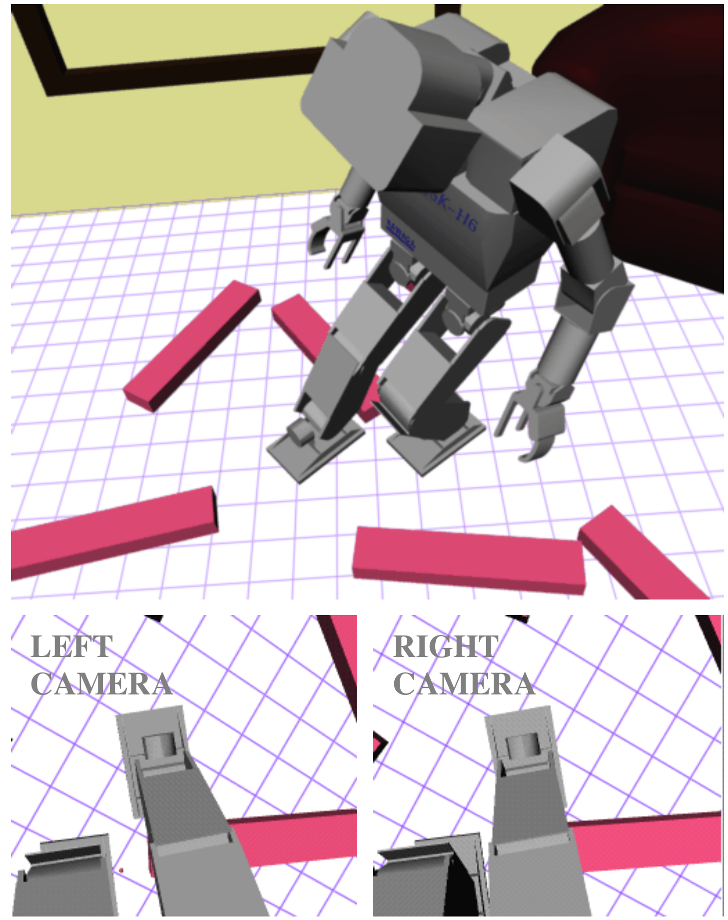




Footstep Placement Planning



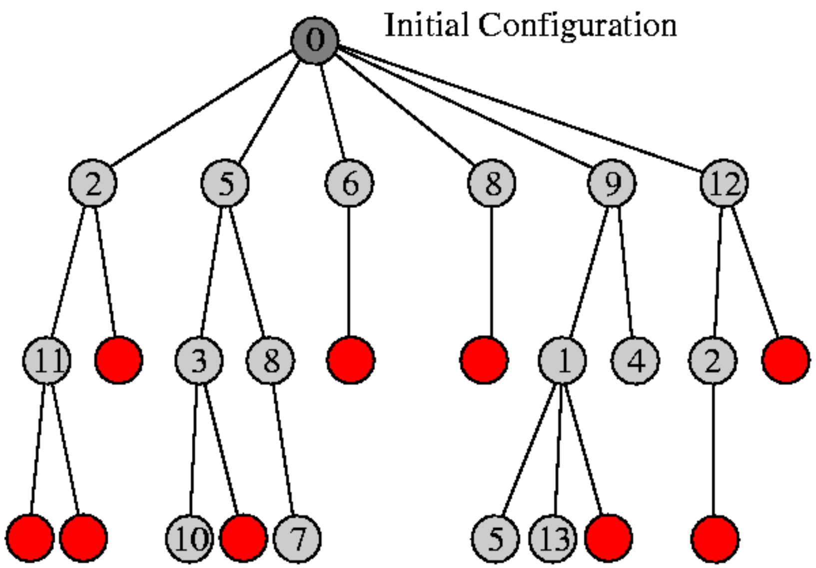
PLANNED FOOTSTEP SEQUENCE

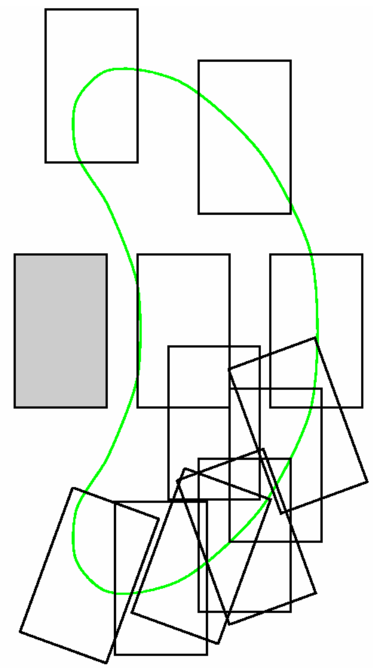


"Footstep planning among obstacles for biped robots"
[Kuffner, Nishiwaki, Kagami, Inaba, Inoue, IROS2001]

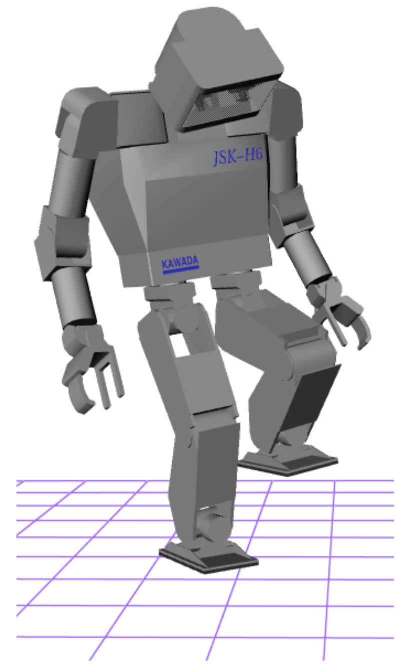
Search Over Possible Footstep Placements

Joel Chestnutt
RI PhD student
2001-2007



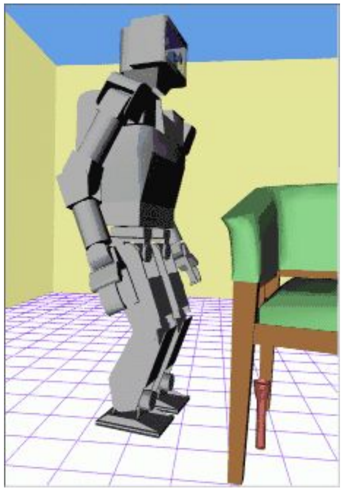


DISCRETE PLACEMENTS



INTERMEDIATE POSTURE

Planning approaches



Plan for all degrees of freedom

Footstep Planning

Abstract away all leg details

Computationally expensive

Uses the full capabilities of the robot

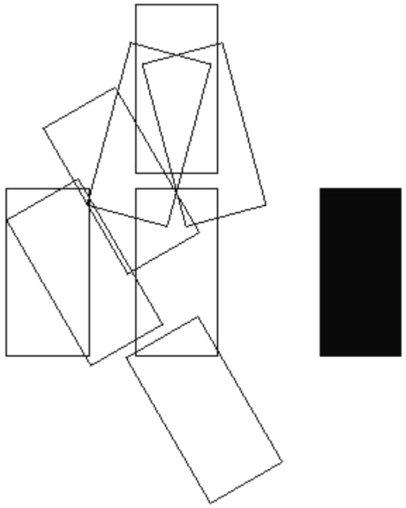
Fast

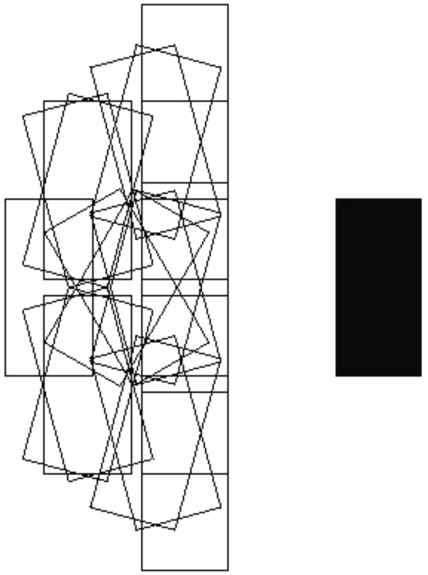
Ignores leg capabilities

Action model based on potential footstep motions

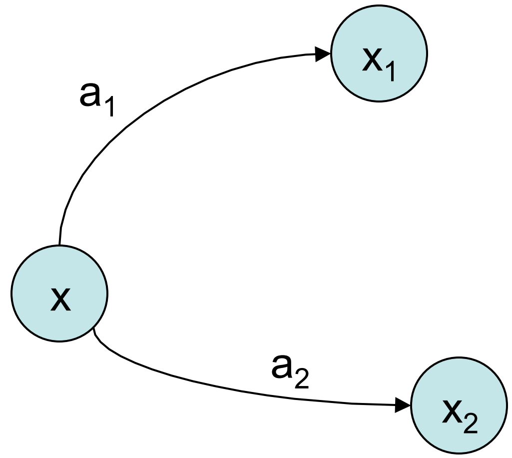
- (x,y,θ) footstep locations relative to stance foot

- Fixed sampling of possible footsteps

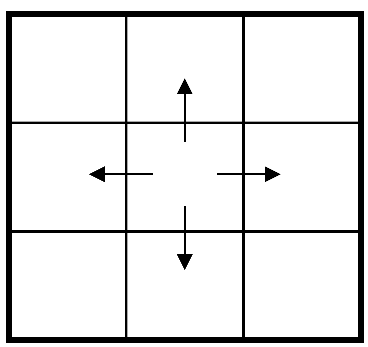


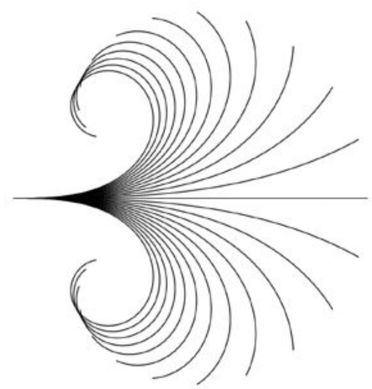


Discrete Planning

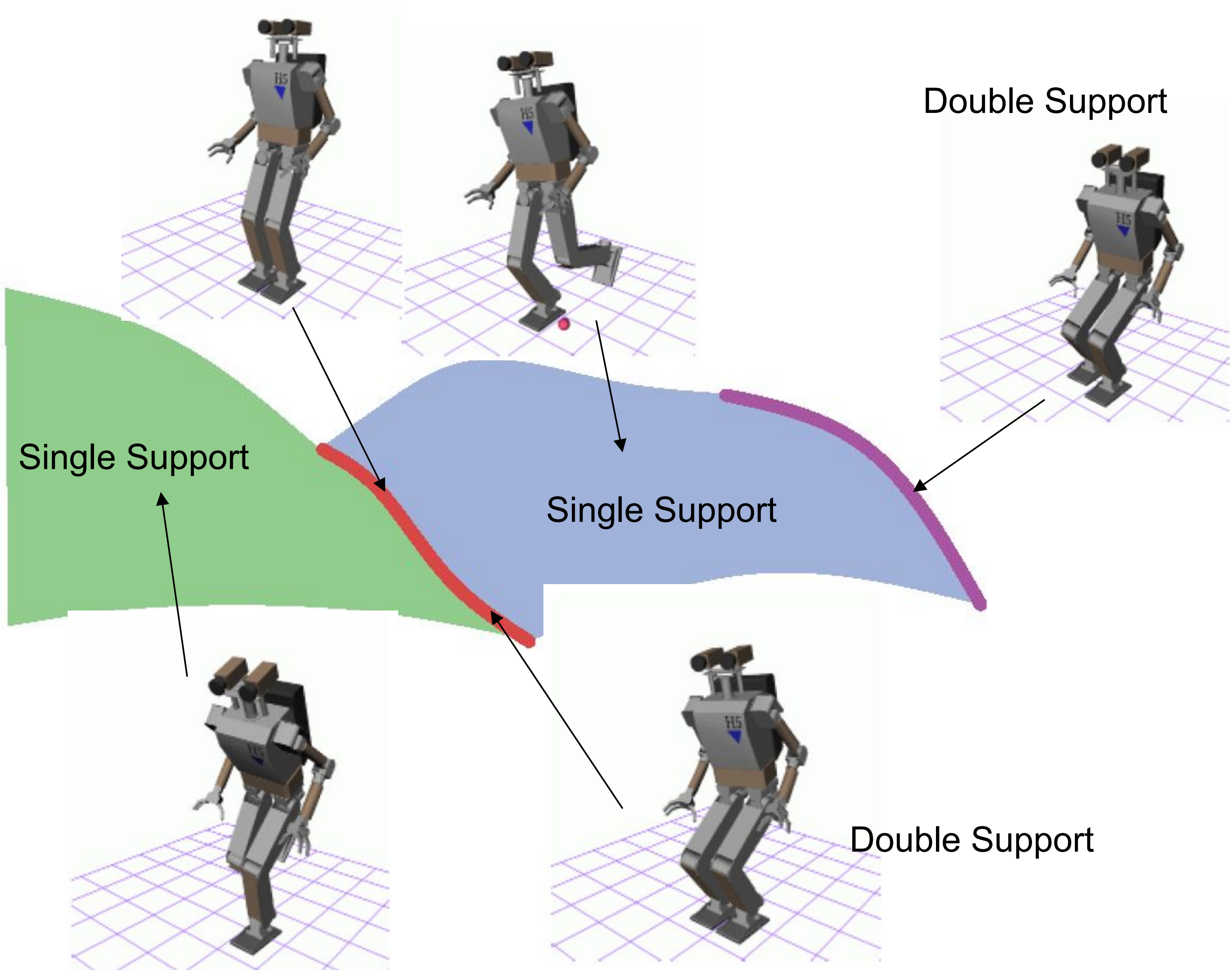


- Input
  $$x_{init}, X_{goal}, e, \mathcal{A}$$
- Successor function
  $$x' = Succ(x, a, e)$$
- How do you choose the set of actions?



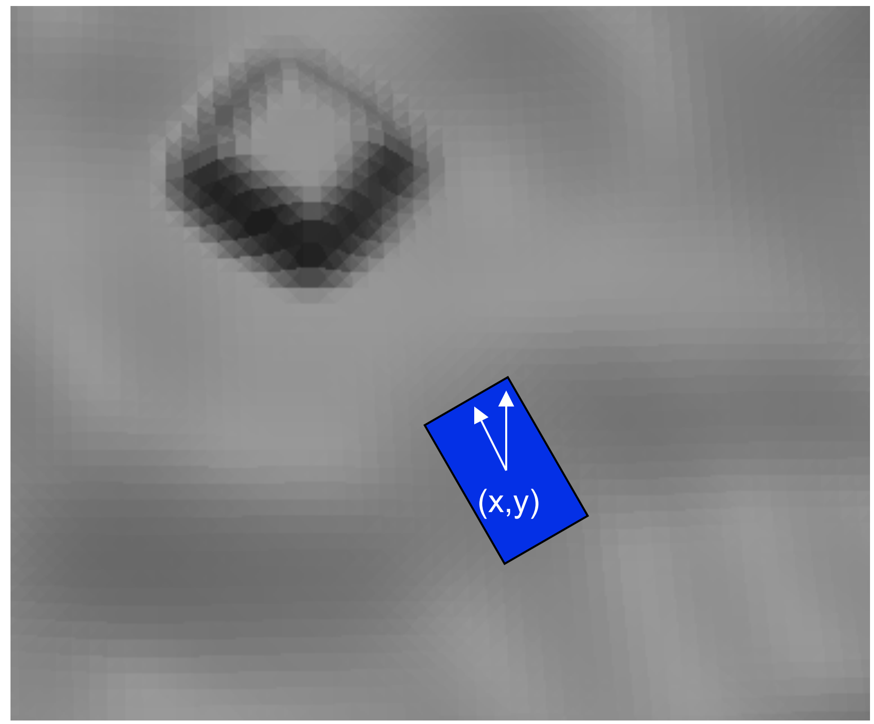


State Space Categorization

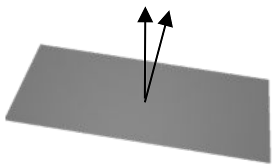
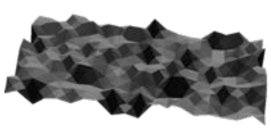
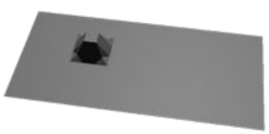
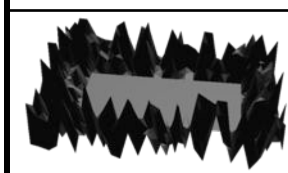


Planner state describes contact configuration

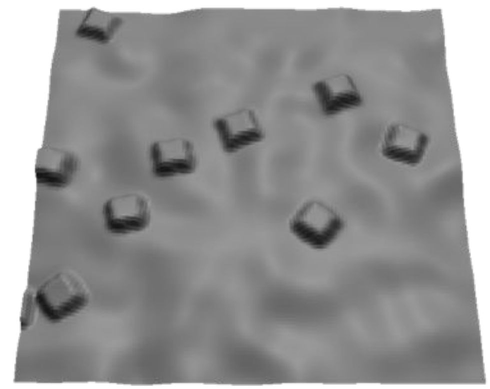
- State Representation:
  - (x, y, θ, leg) of current stance foot
  - roll, pitch, and height determined by terrain shape
- Height map terrain



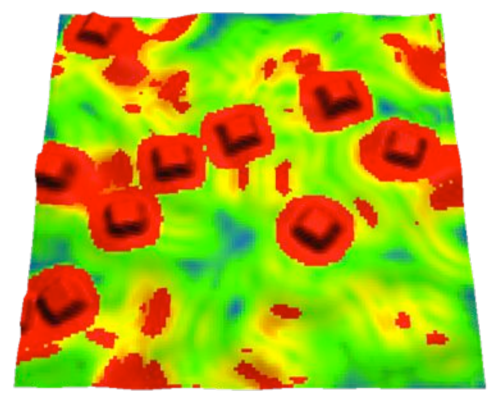
Location Cost

	Angle $\cos^{-1}(n_z)$
	Roughness $\frac{1}{N}\sum_{c\in Cells}\lvert h_c - h_p\rvert$
	Largest Bump $\max_{c\in Cells}(h_c)$
	Stability $\frac{1}{N}\sum_{c\in Cells}[(h_c - h_p)w_c]$
	Safety / Surroundings $\max_{c\in SurrCells}(h_c)$

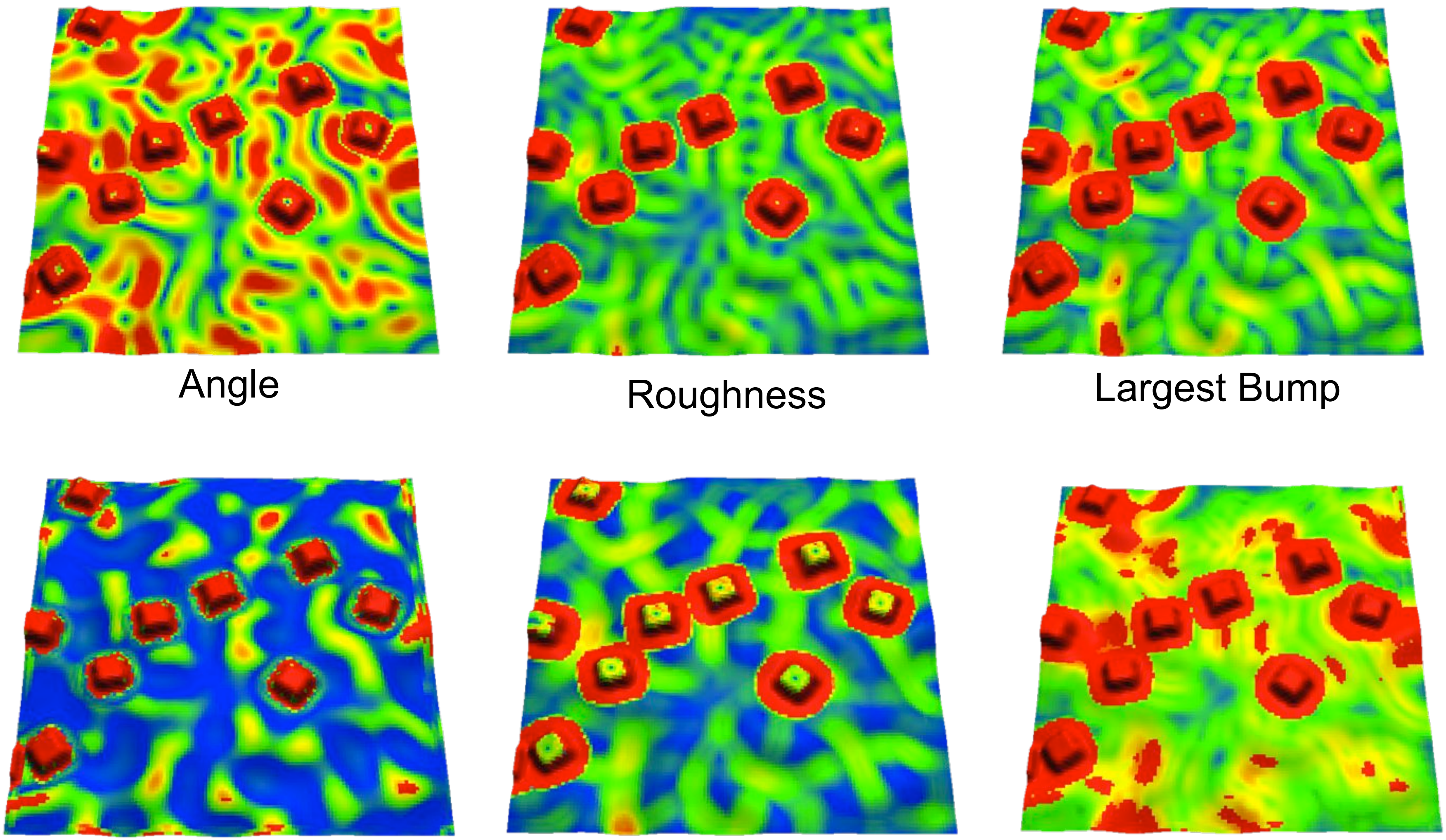
Input Terrain



Metric Evaluation



Location Metrics

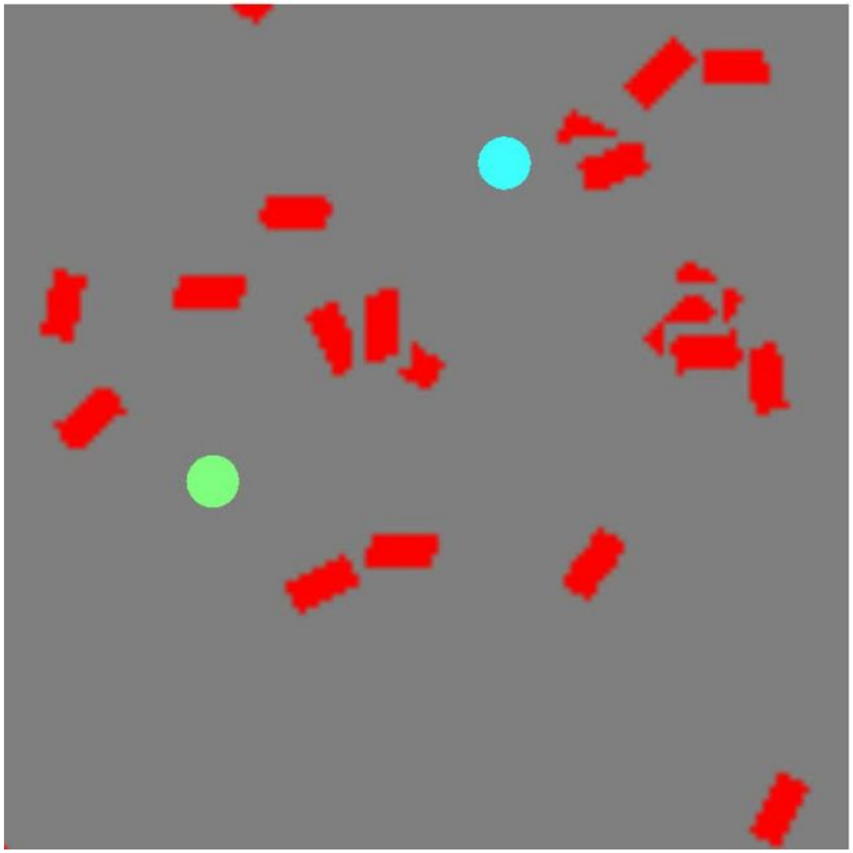


Angle Roughness Largest Bump

Stability Safety All

Search for a Global Footstep Path

PlanPath($s_{init}, s_{goal}, \mathcal{A}, e$)
//Init search (state, cost, expected, parent)
Q.Insert(s_{init}, 0, 0, NULL);
while $running\_time < t_{max}$ **do**
  $s_{best} \leftarrow$ Q.ExtractMin();
  if *GoalReached*(s_{best},s_{goal}) **then**
    return s_{best};
  end
  foreach $a \in \mathcal{A}$ **do**
    $s_{next} \leftarrow s_{best} + a$;
    $c_l \leftarrow$ LocationCost(e, s_{next});
    $c_s \leftarrow$ StepCost(e, a);
    $c_e \leftarrow$ ExpectedCost(e, s_{next});
    Q.Insert(s_{next}, $s_{best}.cost + c_l + c_s, c_e$,
    s_{best});
  end
end



Online Footstep Planning

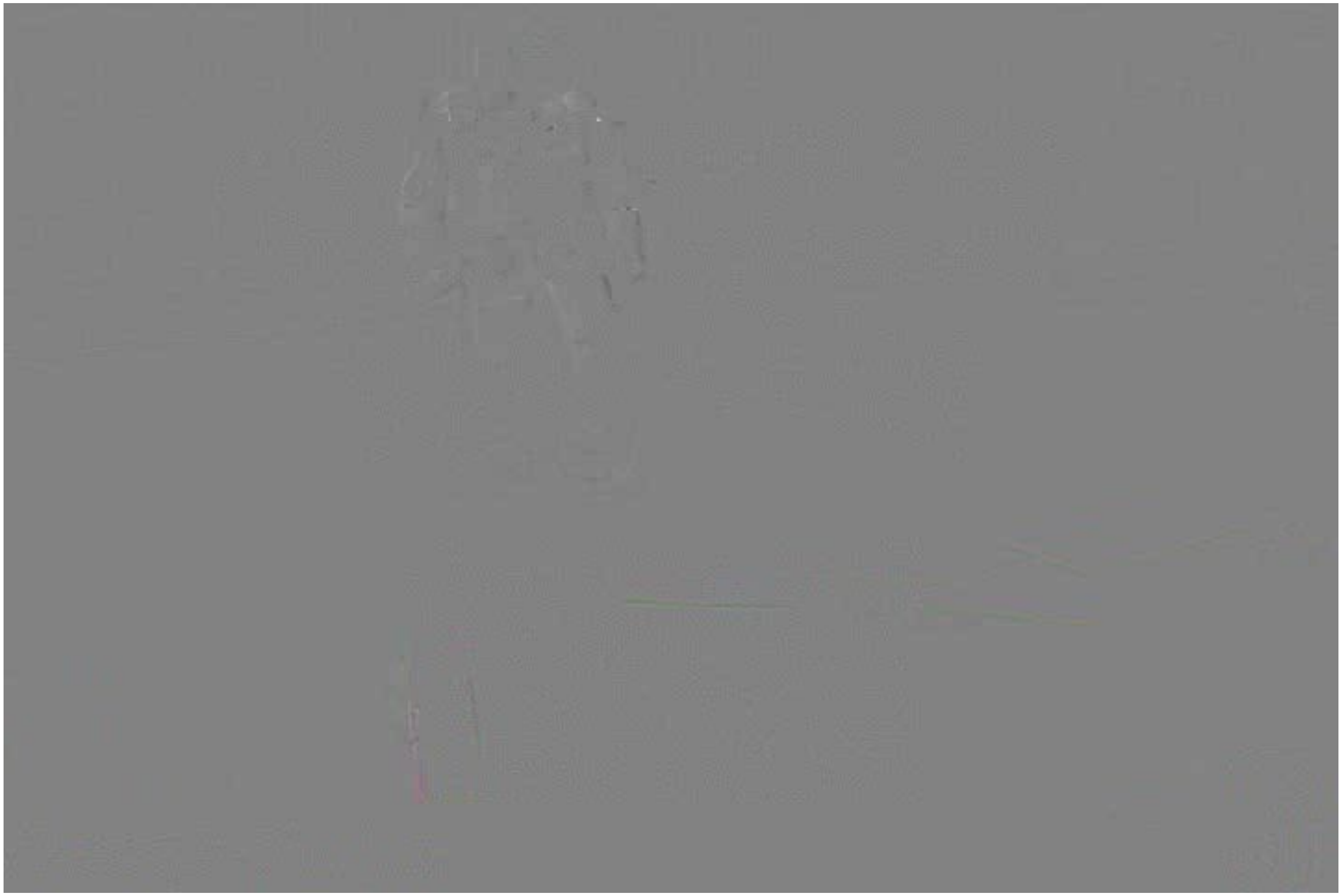
[Kuffner, Nishiwaki, Kagami, Inaba & Inoue, ICRA 2003]

Online Experiments

[Chestnutt, Kuffner, Nishiwaki, Kagami, Inaba & Inoue, 2003]

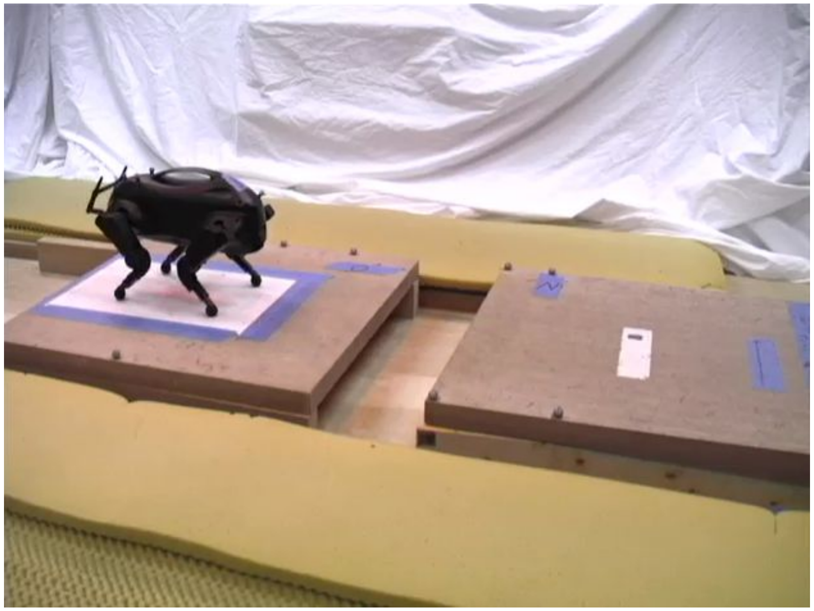
Honda ASIMO at CMU

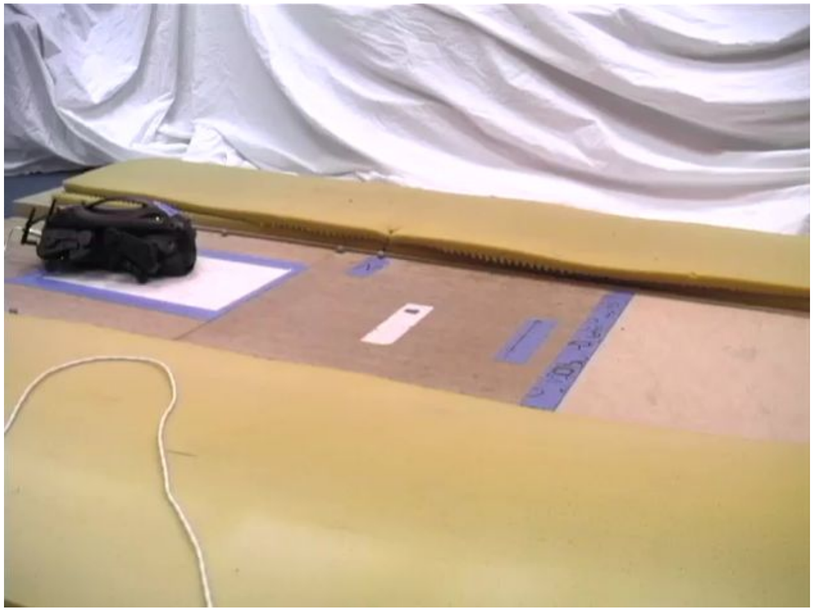
(2004 – 2008)

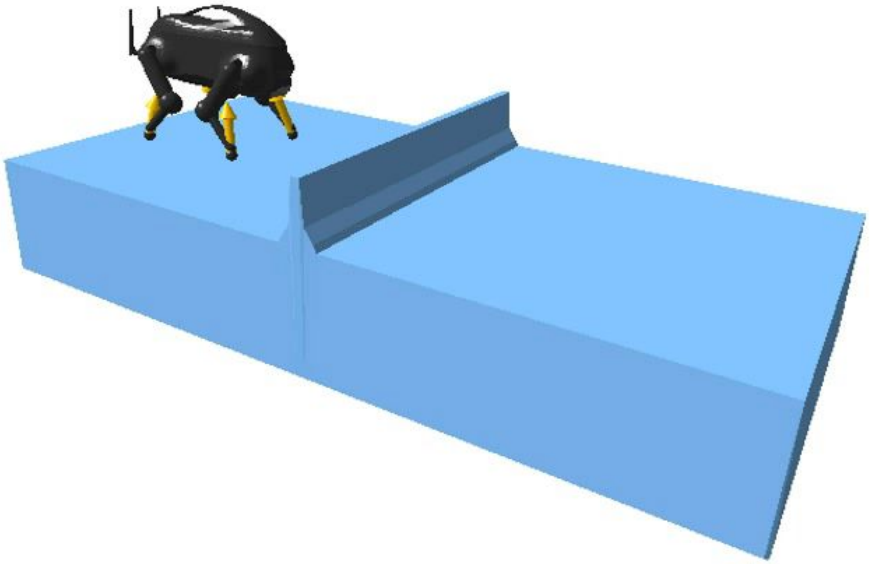


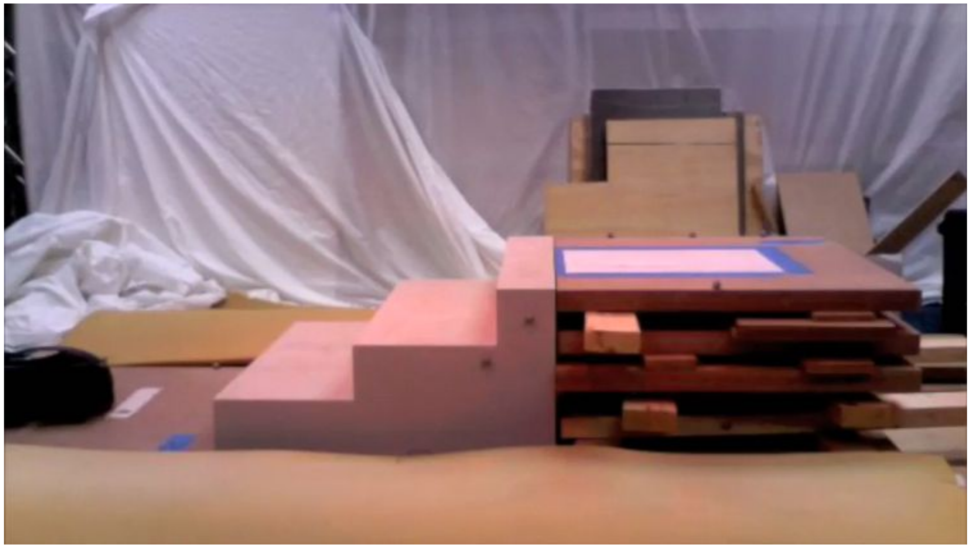
[Chestnutt, Michel, Kuffner, Kanade, IROS 2007]

Planning Dynamic Actions









Key ideas of footstep planning

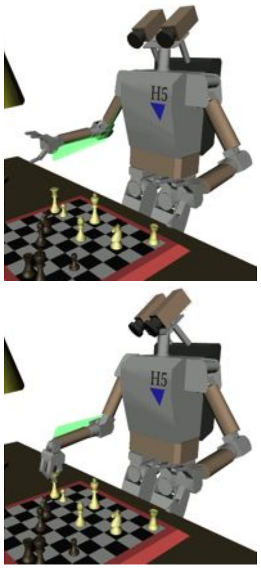
- Plan in the low-dimensional space of contact configurations (stances)
- Approximate path existence between stances by describing the limits of the robot and its controller
- Evaluate stances for stability and properties needed by the controller

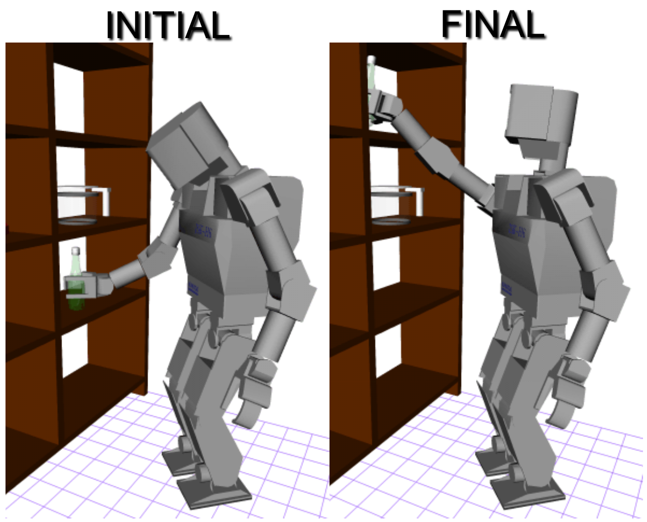
Limitations

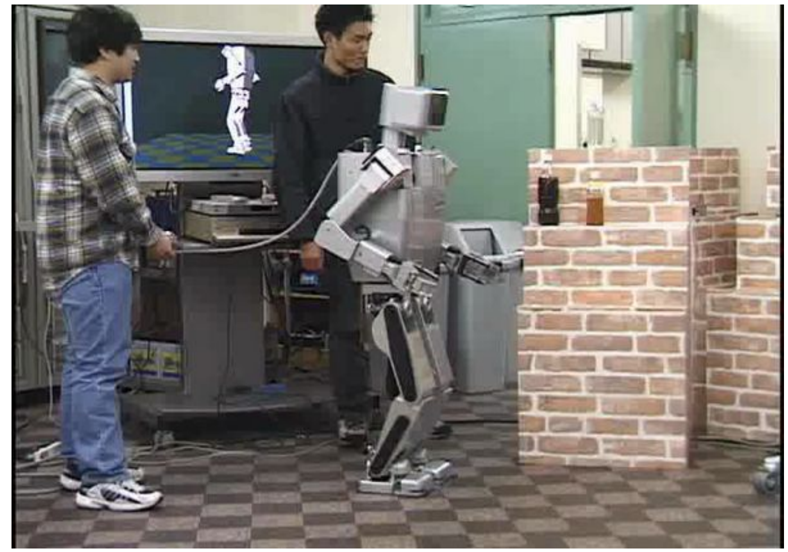
- Does not know anything about the physical makeup (softness, friction, strength) of the world.



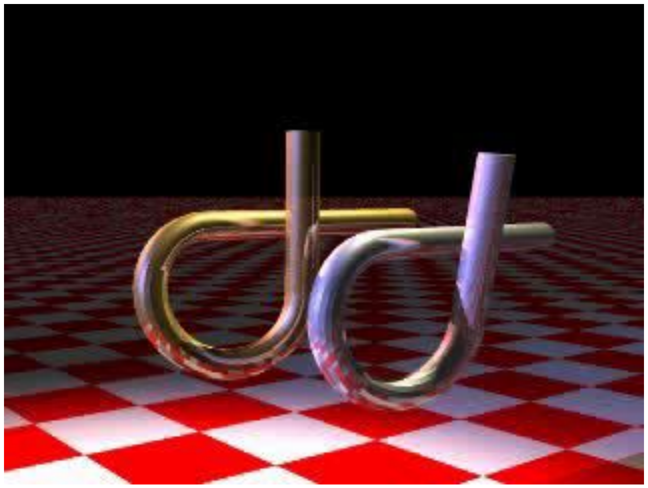
Autonomous Grasping & Manipulation
(2000-2010)

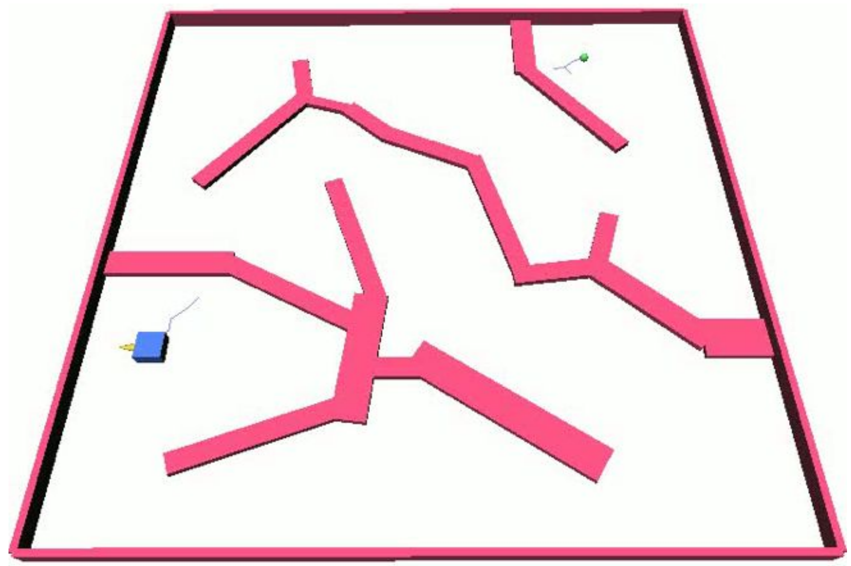




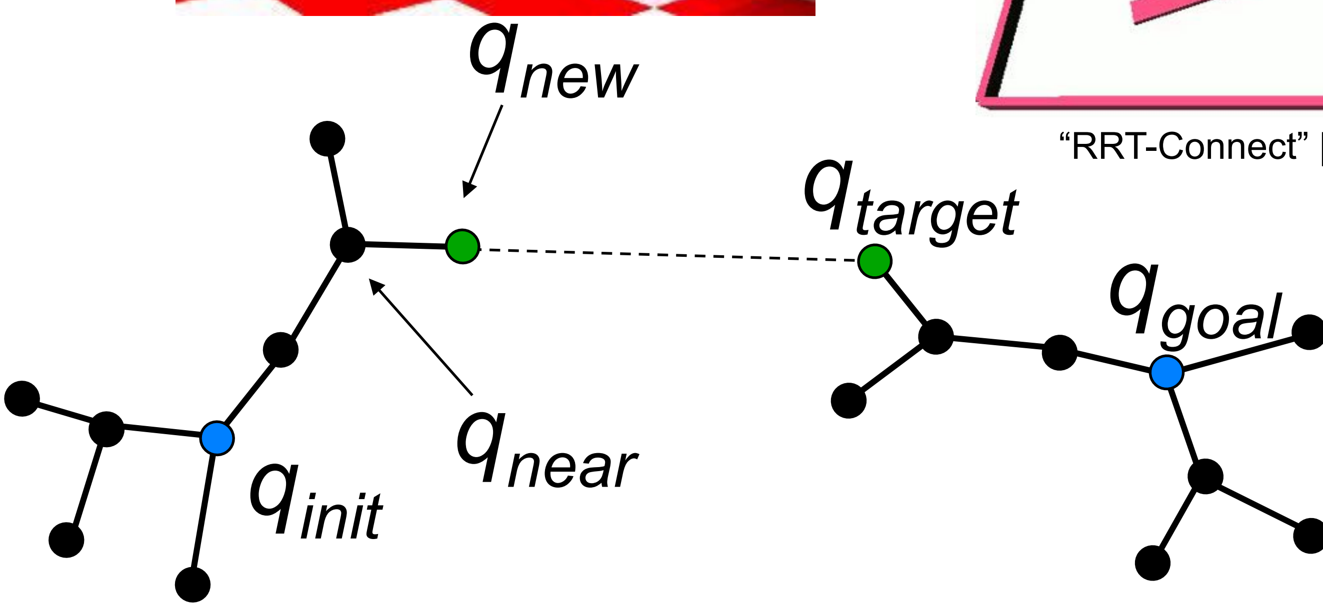


Sampling-Based Planning with Rapidly-exploring Random Trees (RRTs)

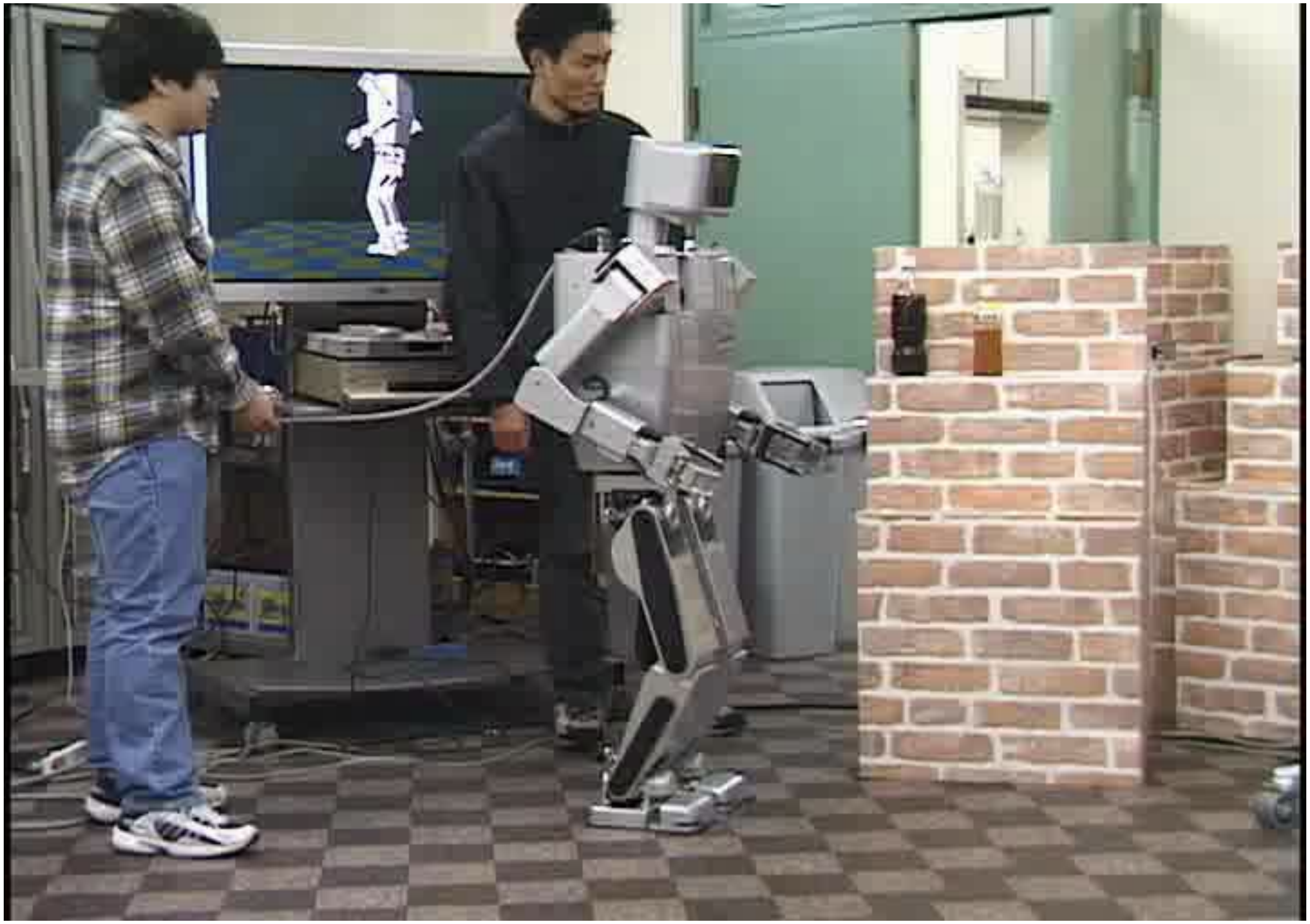




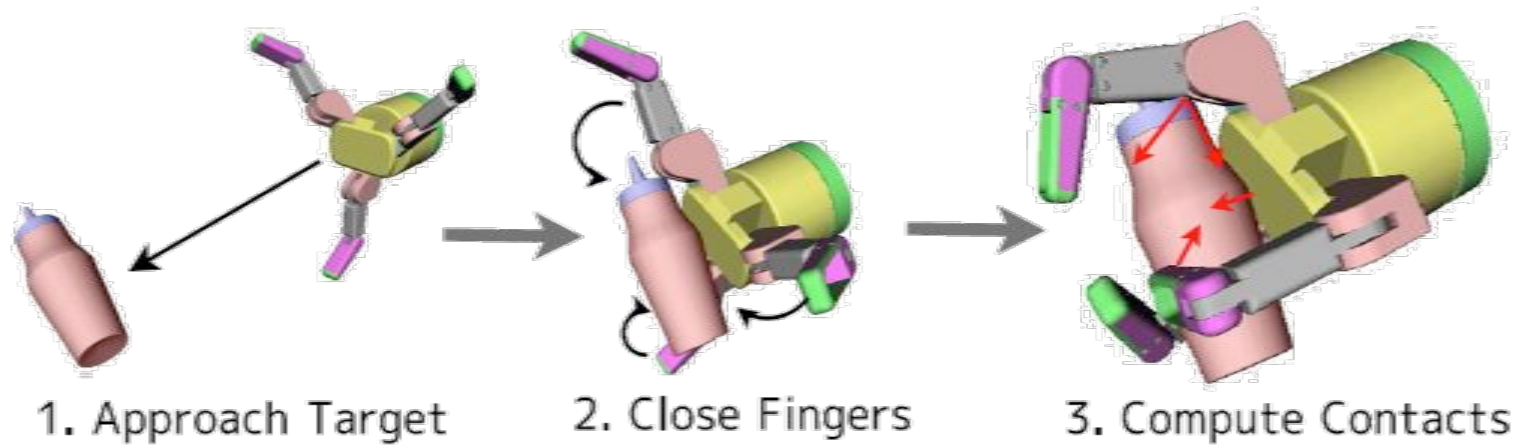
“RRT-Connect” [Kuffner, LaValle ICRA ‘00]

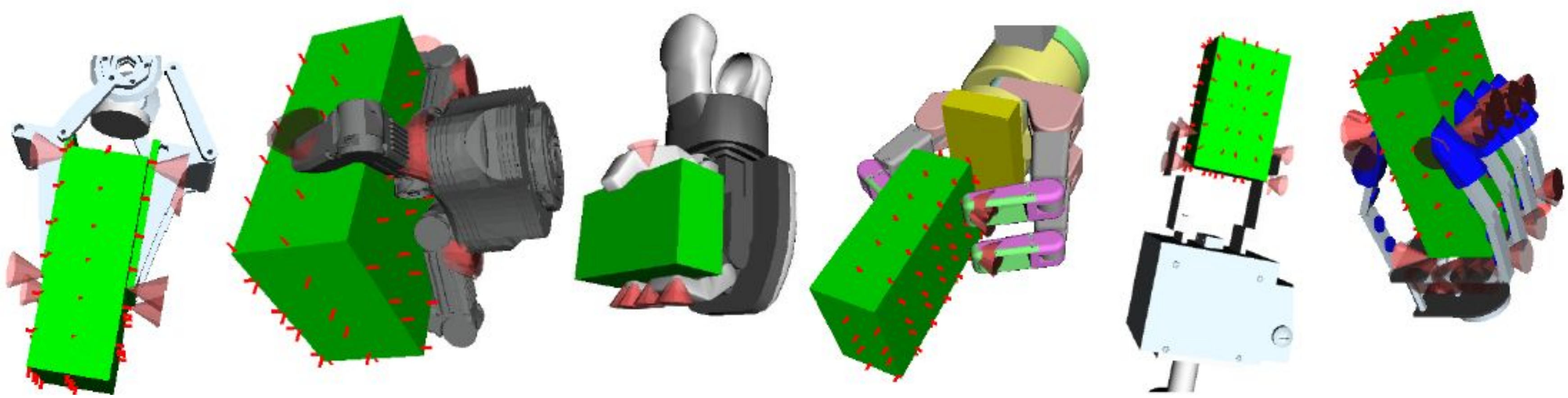


RAVE: Online Manipulation Planning (2001)



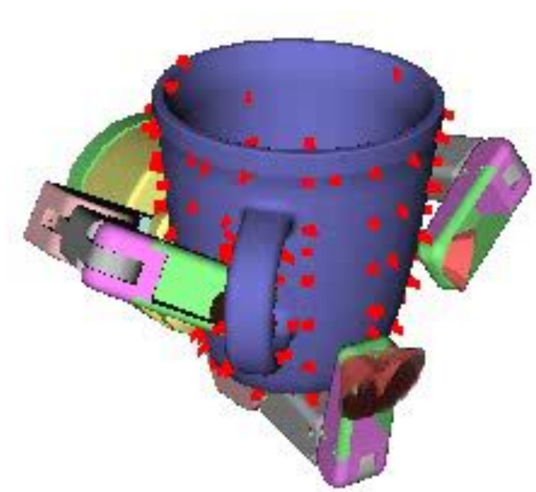
Stable Grasp Generation



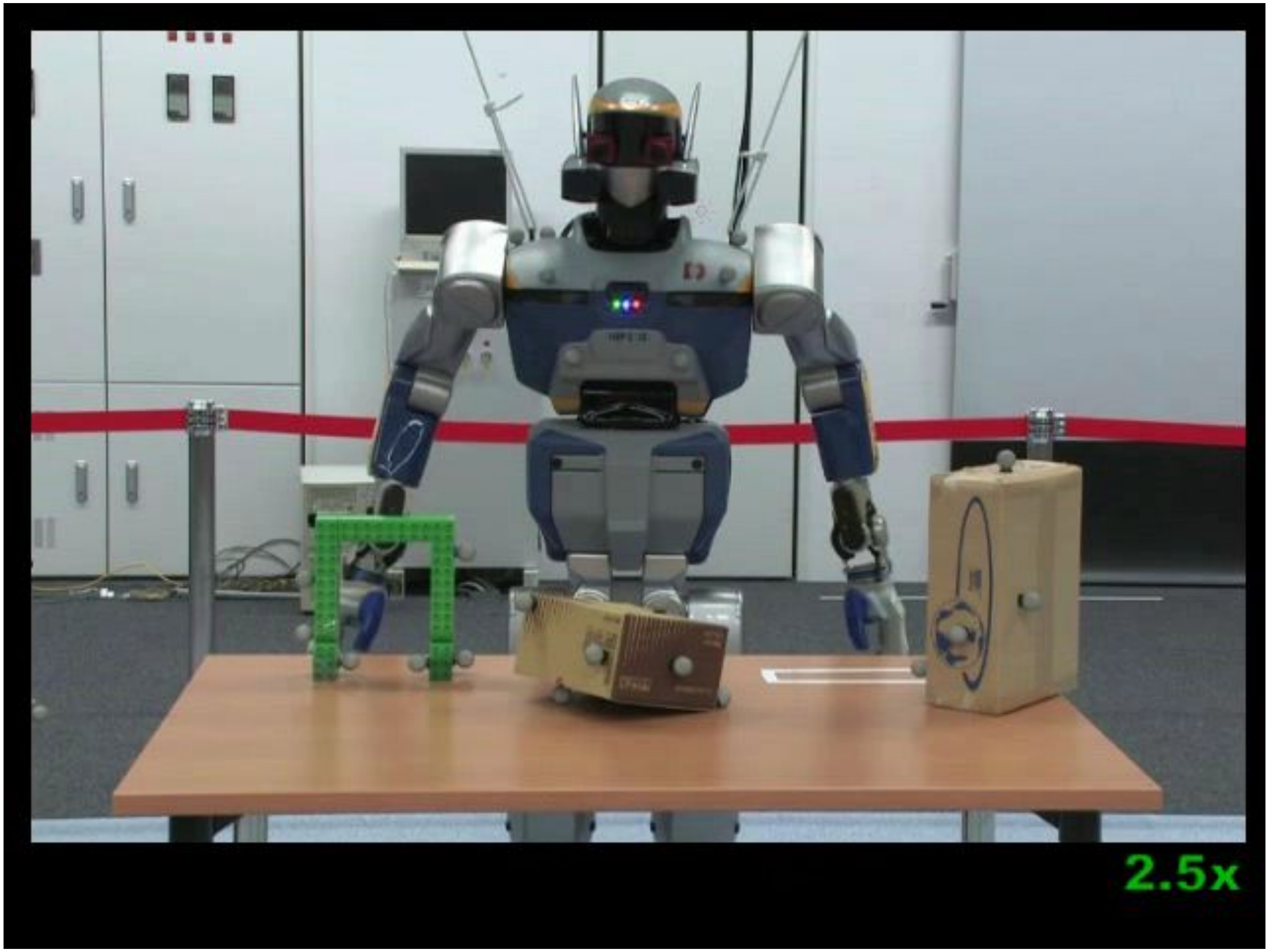


CMU PhD thesis: **Rosen Diankov**

Feasible Grasp Generation



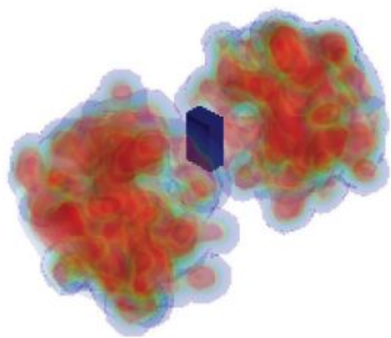
Automatic Regrasping (2006)

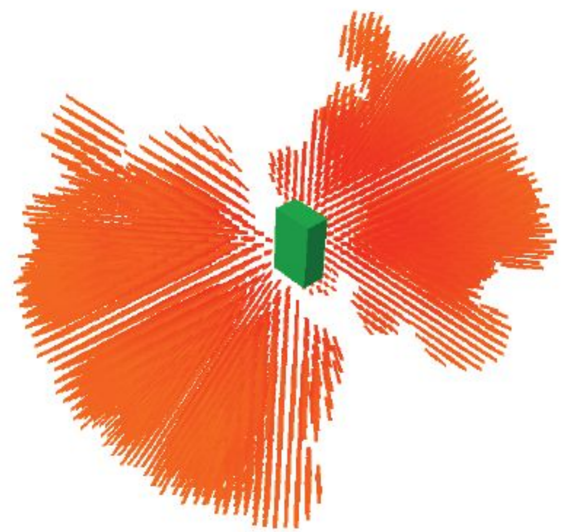


[Berenson, Diankov, Nishiwaki, Kagami, Kuffner] Humanoids2007

Object-Specific 6D Pose Extraction

- Modeling Object Pose Error

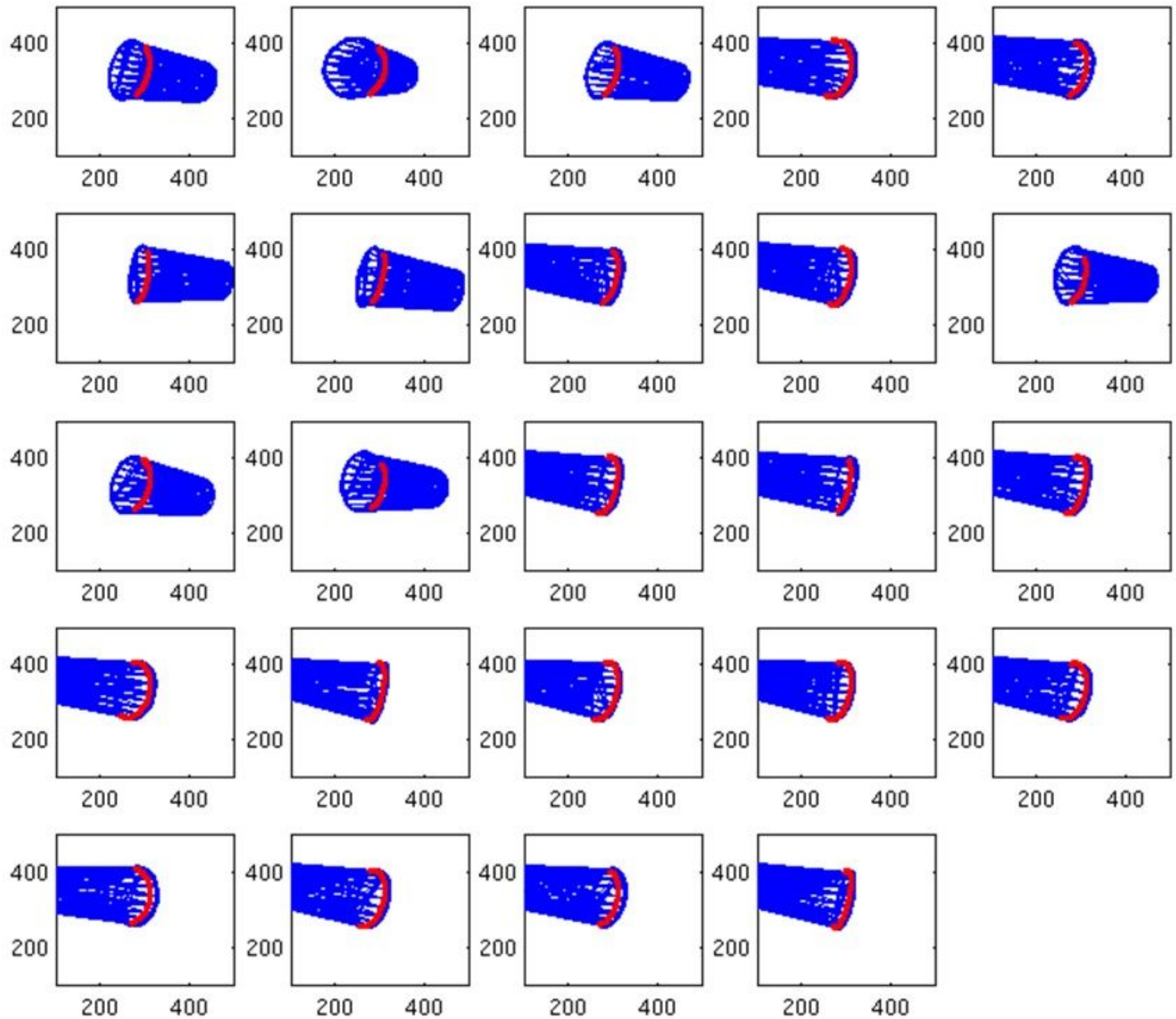




28

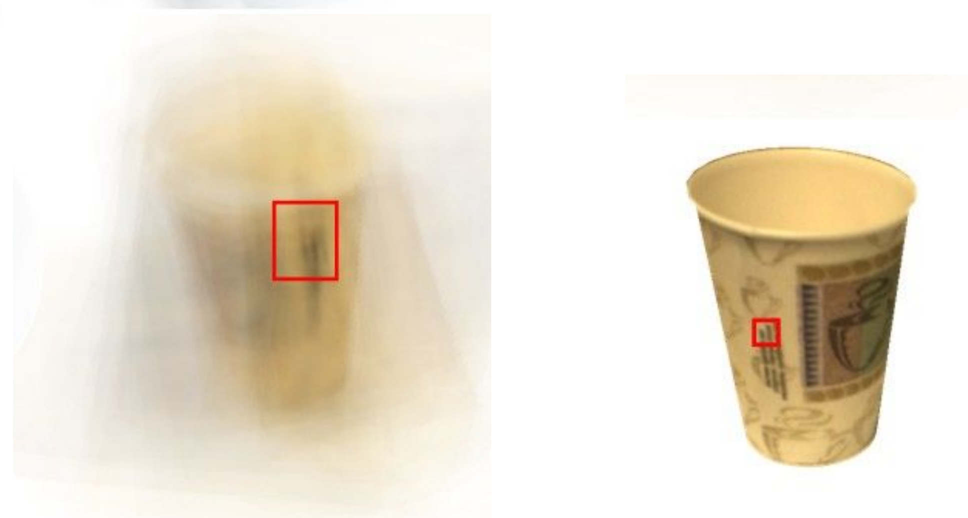
CMU PhD thesis: **Rosen Diankov**

Pose Sets due to a Curve



CMU PhD thesis: **Rosen Diankov**

Mean Images of Induced Pose Sets

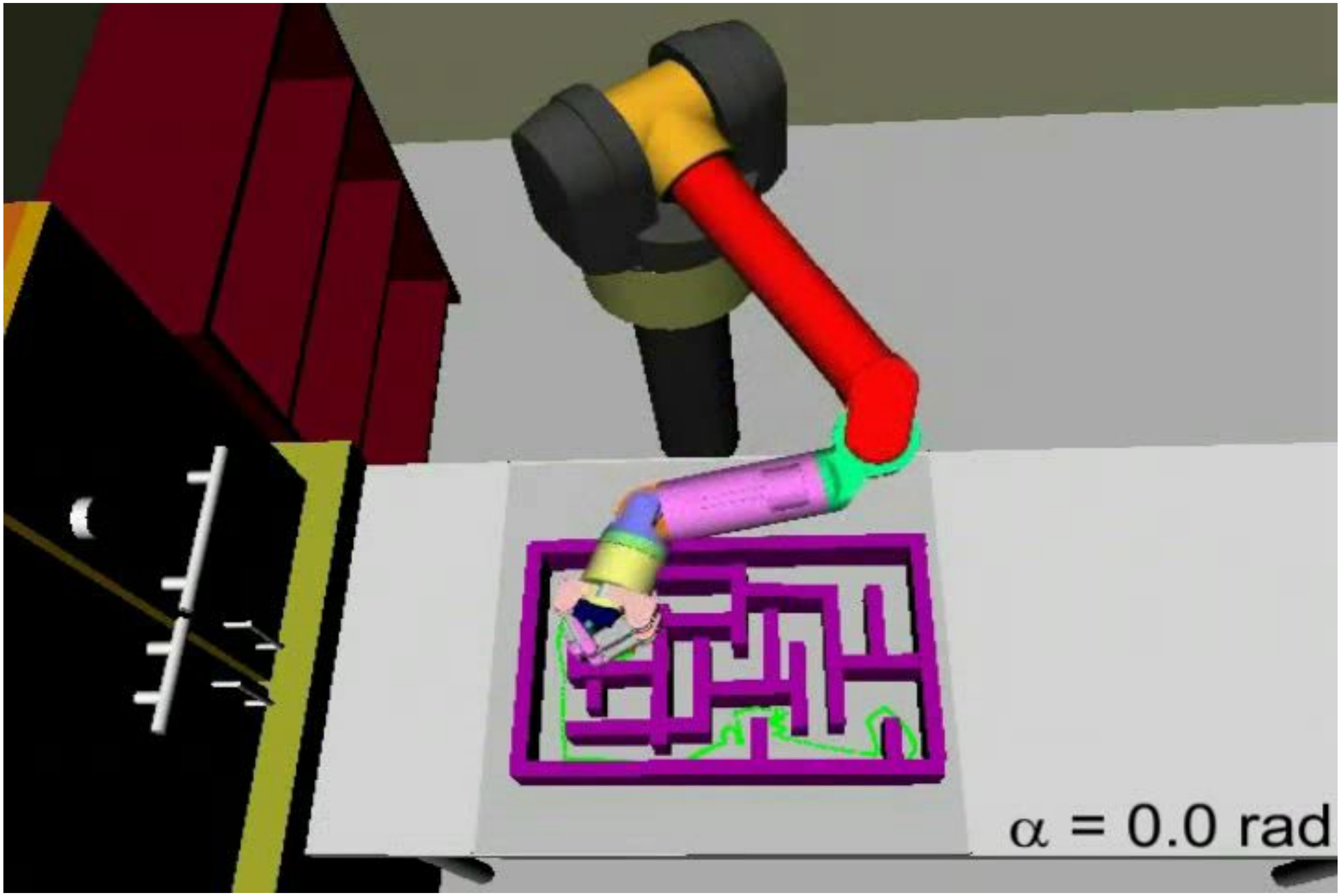


CMU PhD thesis: **Rosen Diankov**

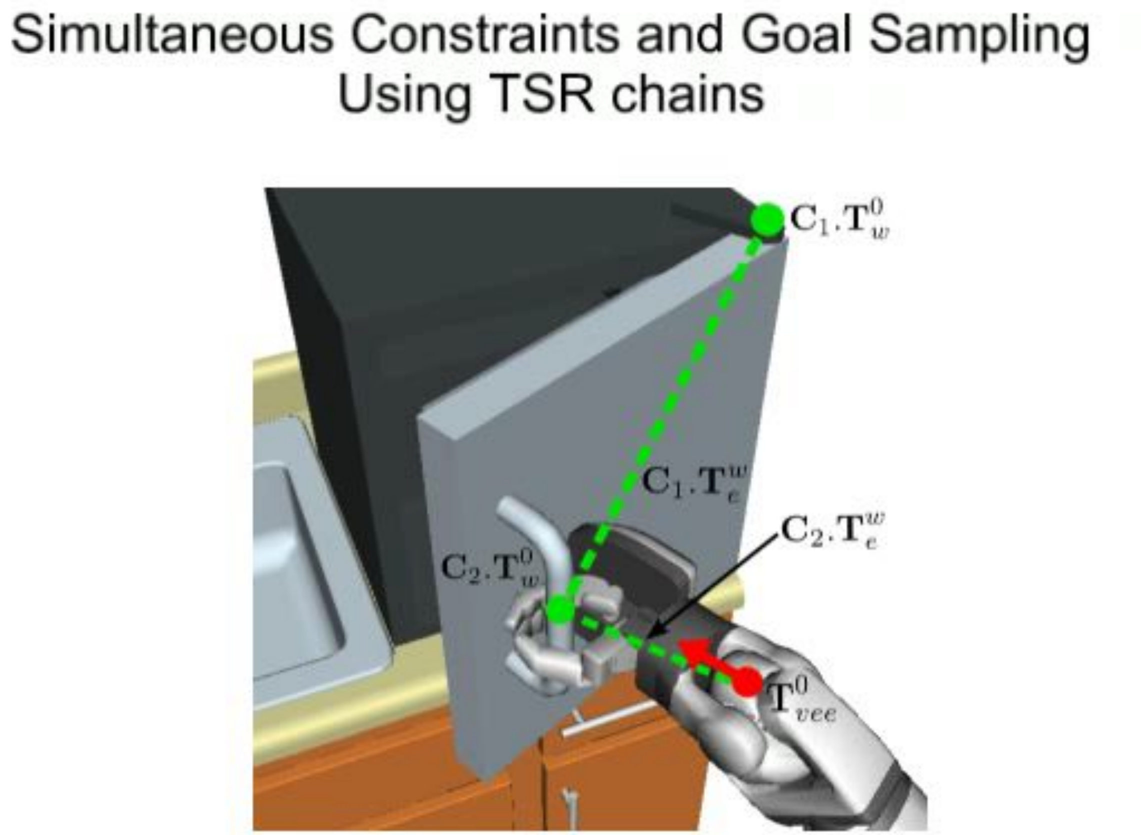
"HERB" : Home-Exploring Robot Butler
(2008 – 2010)

Quality of Life Technology Center
a National Science Foundation Engineering Research Center

Planning With Constraints



Whole-body Constrained Planning



[Berenson, Chestnutt, Srinivasa, Kagami, Kuffner , *Humanoids2009*]

Self-driving Cars

The New York Times

Science

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SMARTER THAN YOU THINK

Google Cars Drive Themselves, in Traffic

Ramin Rahimian for The New York Times

Dmitri Dolgov, a Google engineer, in a self-driving car parked in Silicon Valley after a road test.

By JOHN MARKOFF
Published: October 9, 2010

MOUNTAIN VIEW, Calif. — Anyone driving the twists of Highway 1 between San Francisco and Los Angeles recently may have glimpsed a Toyota Prius with a curious funnel-like cylinder on the roof. Harder to notice was that the person at the wheel was not actually driving.

RECOMMEND

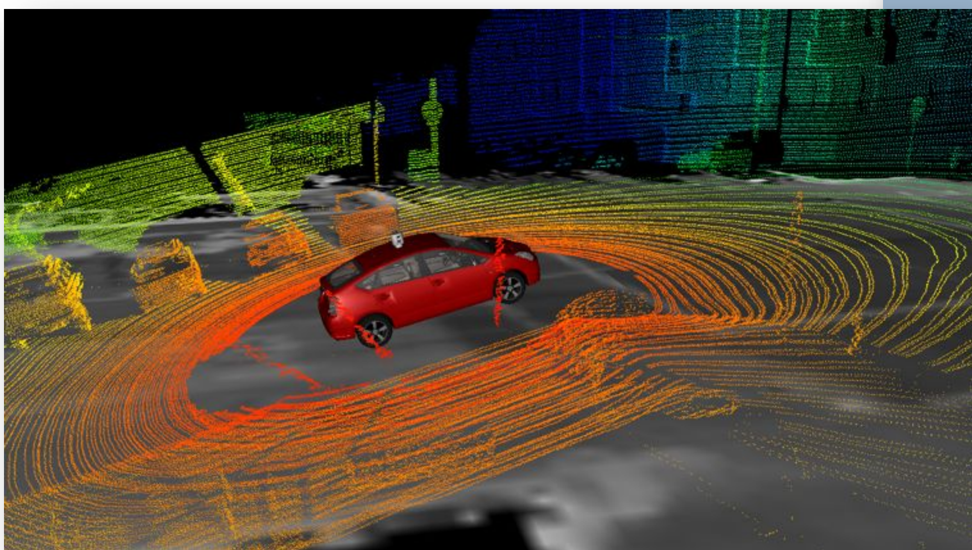
TWITTER

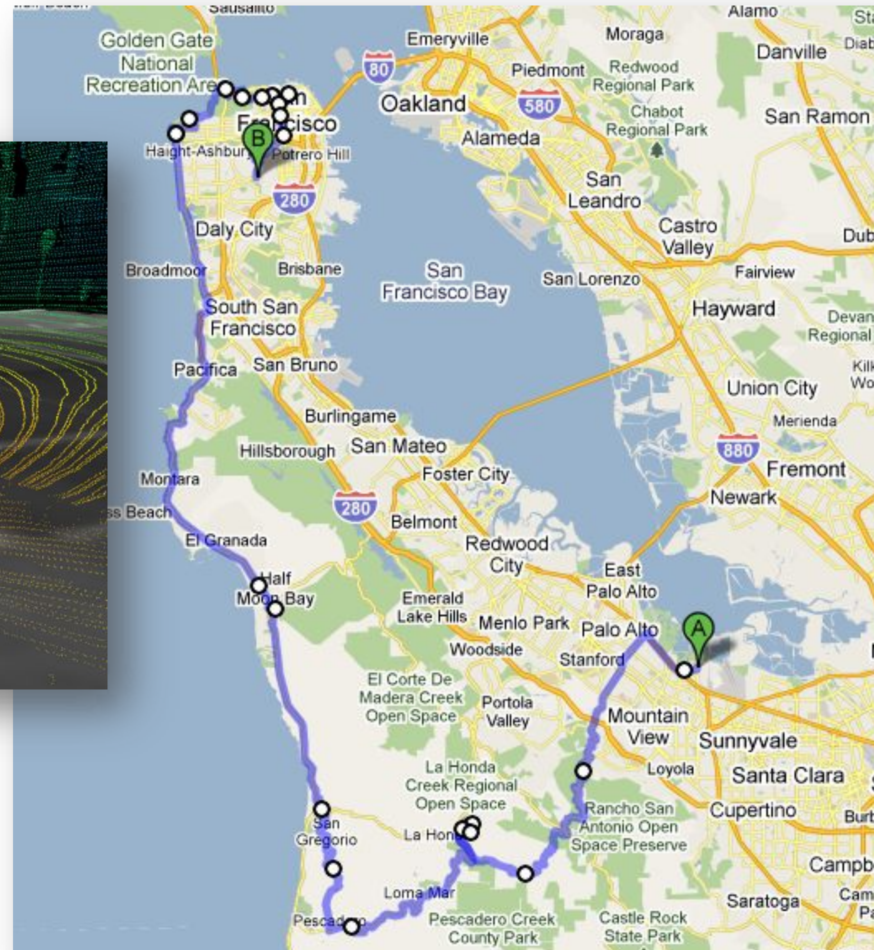
COMMENTS (85)

SIGN IN TO E-MAIL

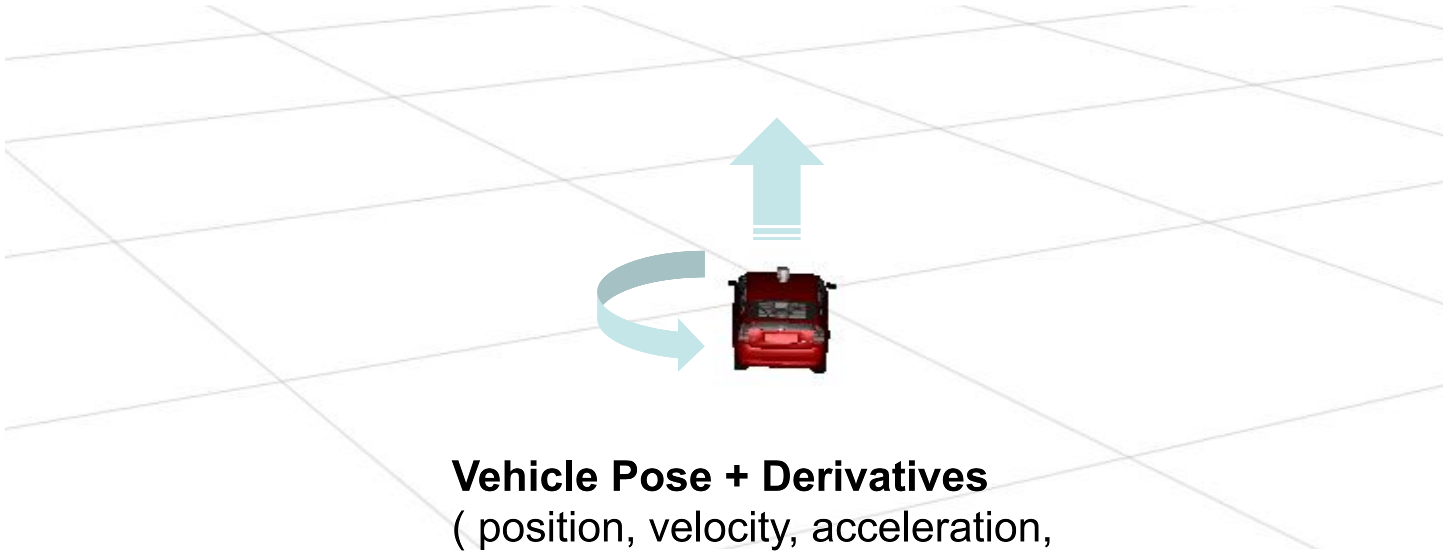
Accomplishments

- A total of more than 145,000 autonomous miles
- 10 high-complexity routes of roughly 100 miles each without human intervention.





Planning State for a Robot Car



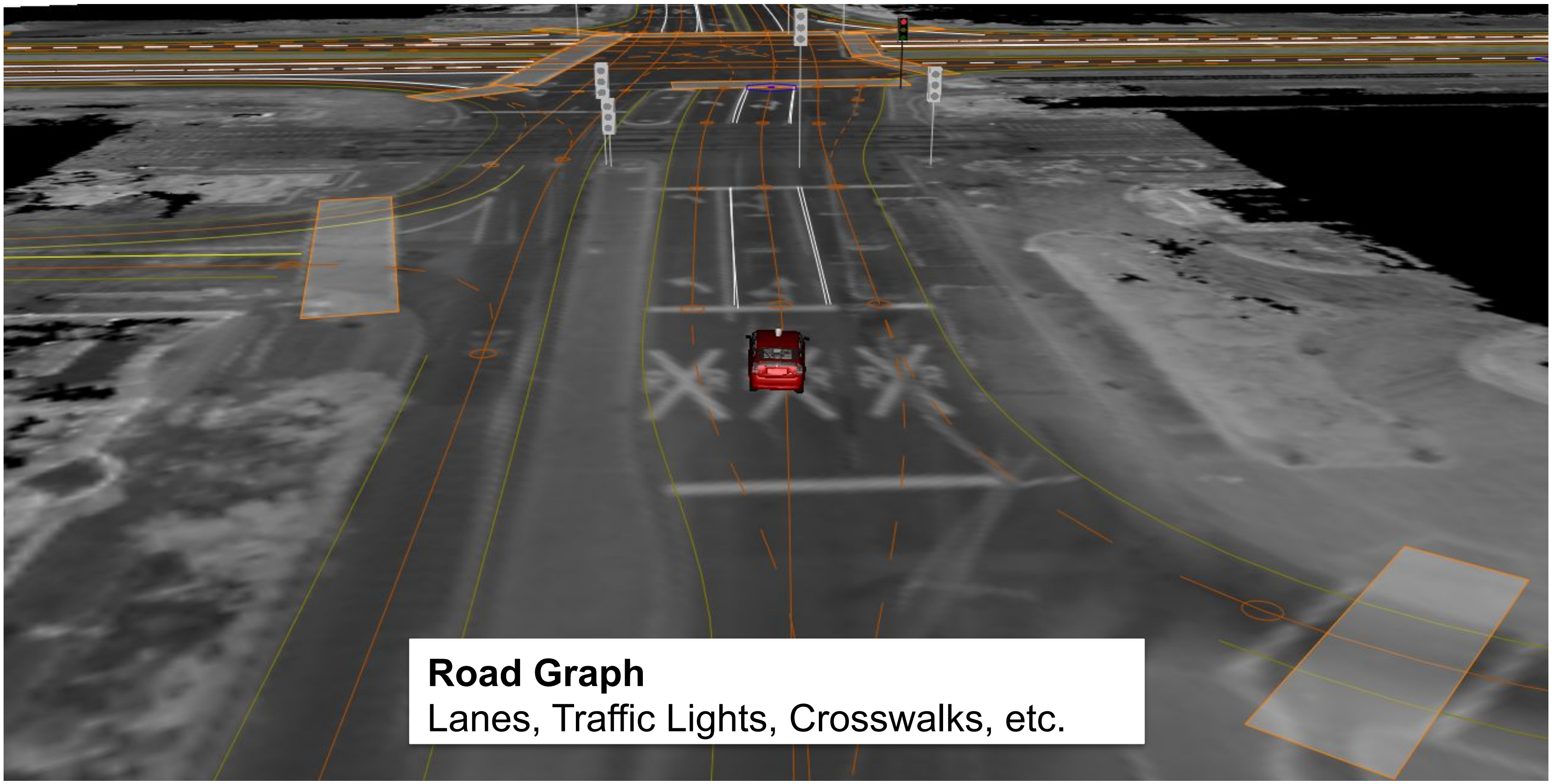
Vehicle Pose + Derivatives
(position, velocity, acceleration,
orientation, angular vel, angular accel)

- High-dimensional in principle
- **Driving model abstraction** greatly reduces the dimensionality (i.e. speed up, slow down, change lane)

Driving Model Abstraction

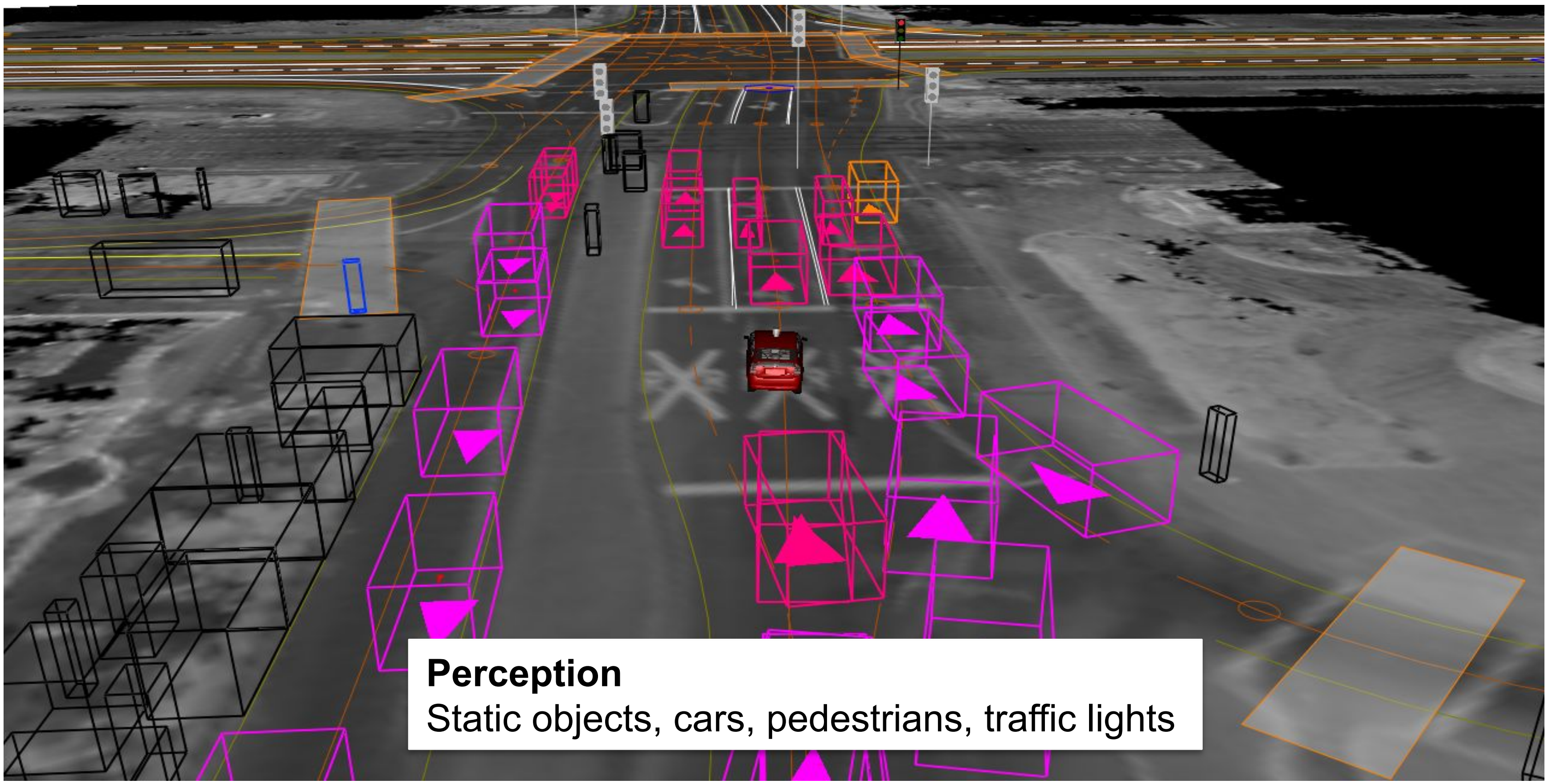
Mike Montemerlo, Andrew Chatham

Driving Model Abstraction



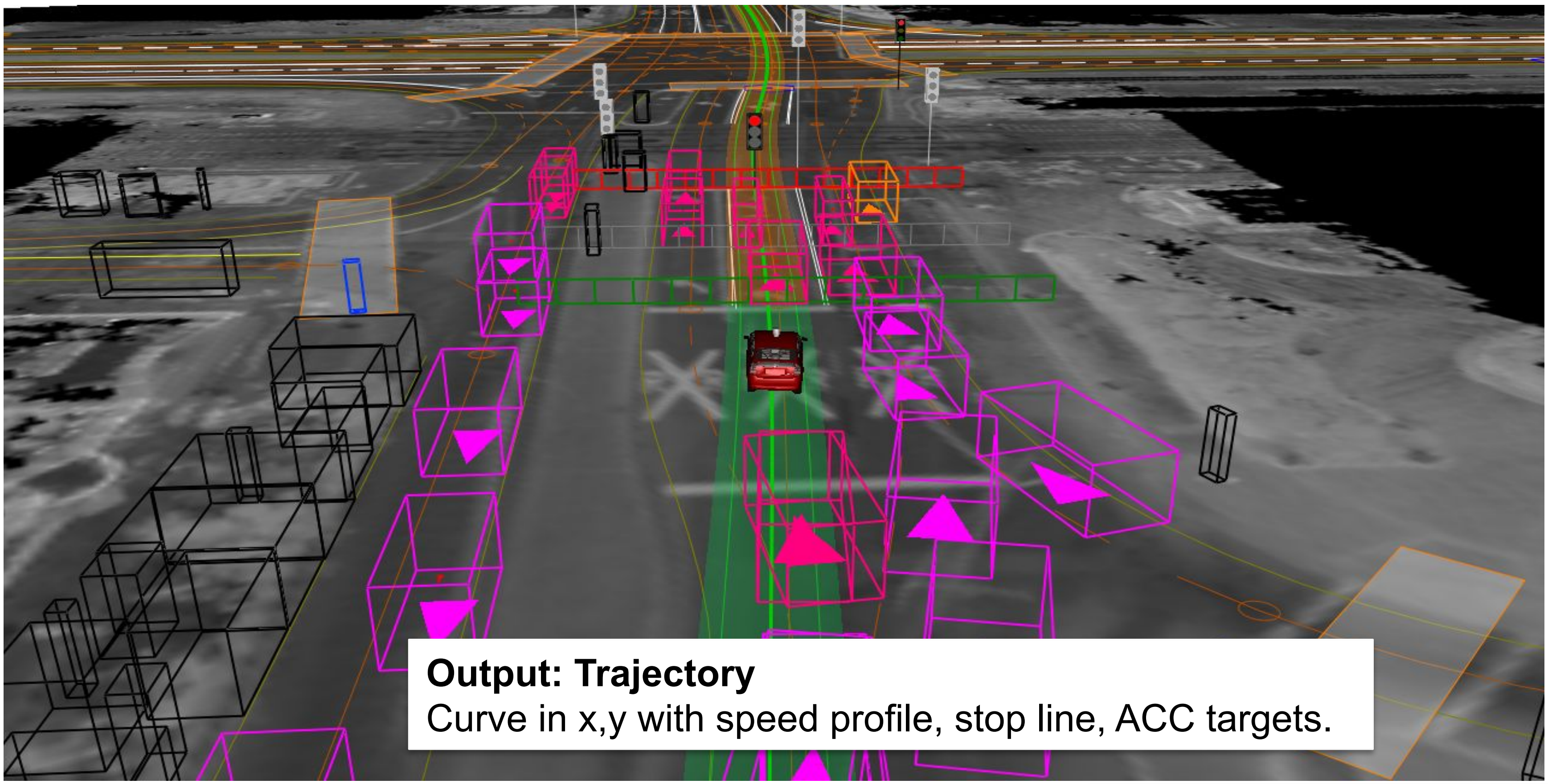
Road Graph
Lanes, Traffic Lights, Crosswalks, etc.

Driving Model Abstraction



Jiajun Zhu, Nathaniel Fairfield, Russell Smith, Hector Yee, Dirk Haehnel

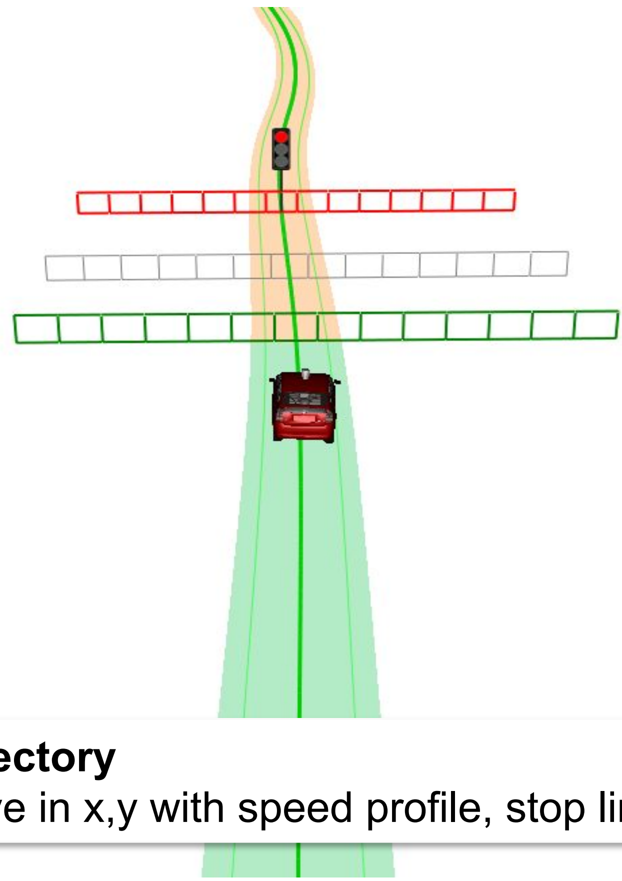
Driving Model Abstraction



Output: Trajectory
Curve in x,y with speed profile, stop line, ACC targets.

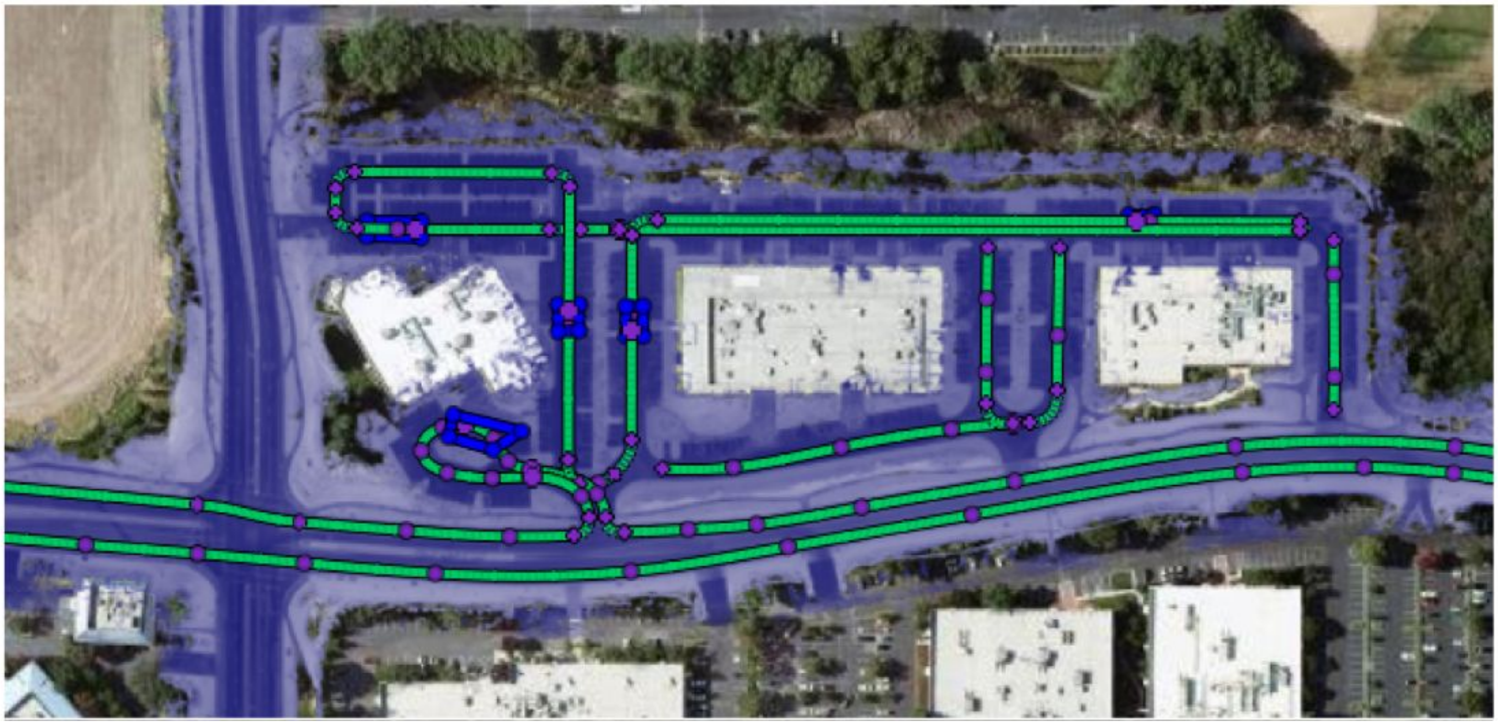
Dmitri Dolgov, Chris Urmson

Trajectory Planning



Trajectory
Curve in x,y with speed profile, stop line, ACC targets.

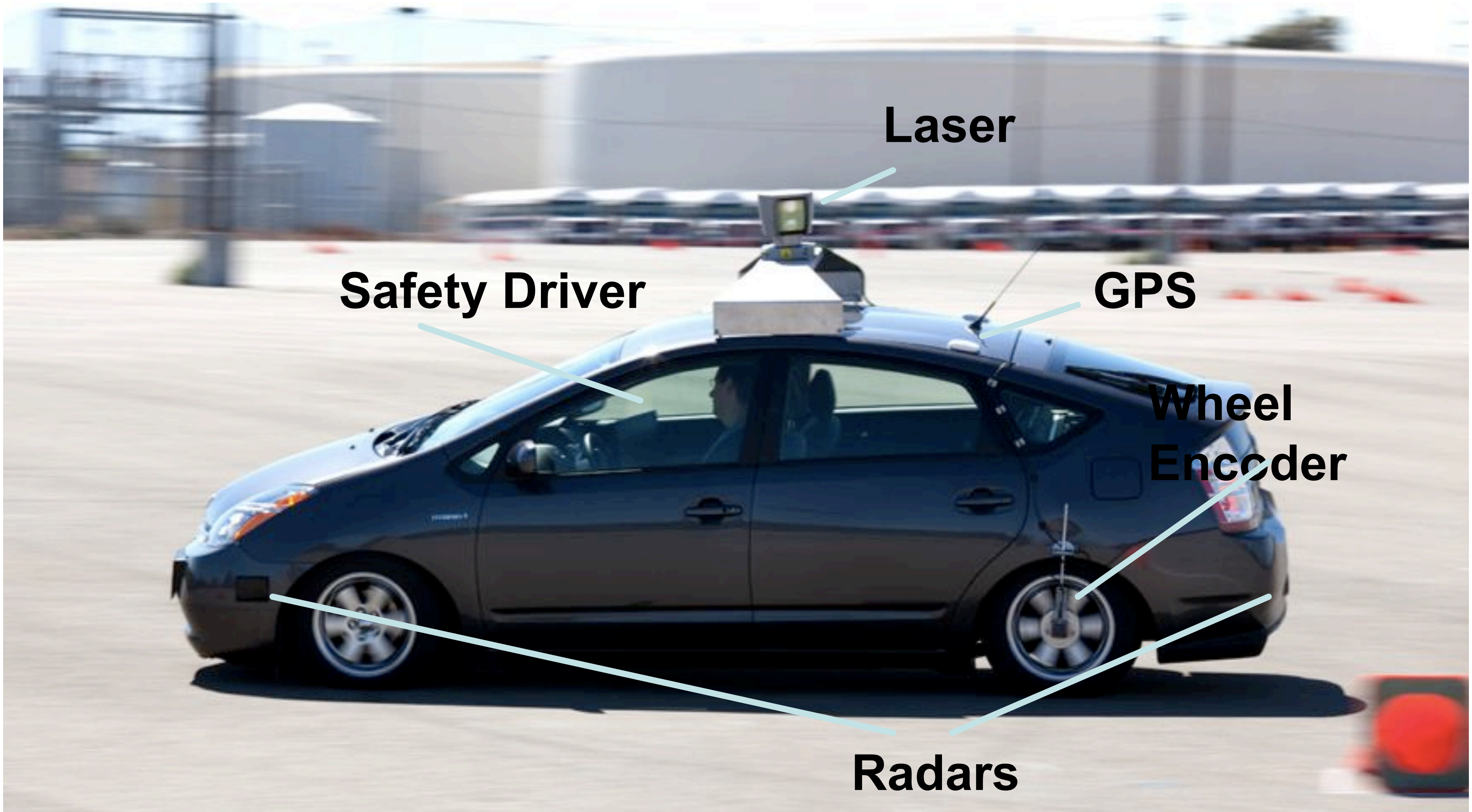
Route Planning



- Minimize overall route complexity
  (lane changes, unprotected left turns, no U-turns)
- Route duration used as additional metric

James Kuffner, Hy Murveit

A Self-Driving Prius



Engineering Team

Summary

- Motion planning techniques can be made practical, useful, and even essential for physical robots.
- Model reduction is a powerful tool for making planning tractable.
- Need to think carefully about proper abstractions
  - Discretization of state and actions
  - Representing prior models