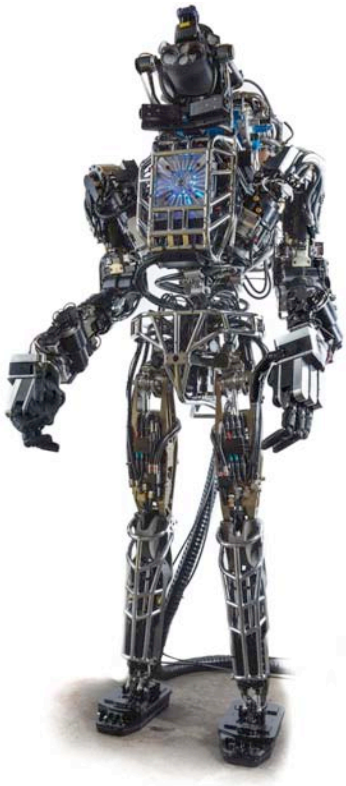


MIT's entry into the **DARPA Robotics Challenge**

Russ Tedrake

groups.csail.mit.edu/locomotion


FAIRPLEX
FAIRPLEX

DARPA Robotics "Grand" Challenges

- 2004/5 - DARPA Grand Challenge
- 2007 - DARPA Urban Challenge
- Self-driving car projects at every major auto manufacturer, Google, Uber, Apple, ...

- 2012 - time for a new challenge?

Courtesy of Daniel Suarez. Used with permission.

DARPA Robotics Challenge Kick Off

Posted 25 Oct 2012 at 19:46 UTC by steve

DARPA has announced the start of the next DARPA Robotics Challenge. This time, the goal is to develop ground robots that perform complex tasks in "dangerous, degraded human-engineered environments". That means robots that perform humanitarian, disaster relief operations. The robots must use standard human hand tools and vehicles to navigate a debris field, open doors, climb ladders, and

The DARPA Robotics Challenge

Official challenge: Disaster response (Fukushima Daiichi nuclear disaster)

My take: Evaluate (and advance) state-of-the-art in **mobile manipulation**

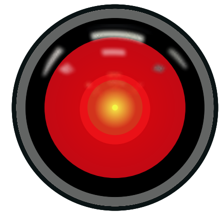
- Incredible new hardware from industry (esp. Boston Dynamics)

- Research: Relatively sophisticated algorithms on relatively modest hardware
- Mashup!

A twist: Graded Autonomy

Allow a human operator, but with a degraded network connection

Teleoperation



Complete Autonomy

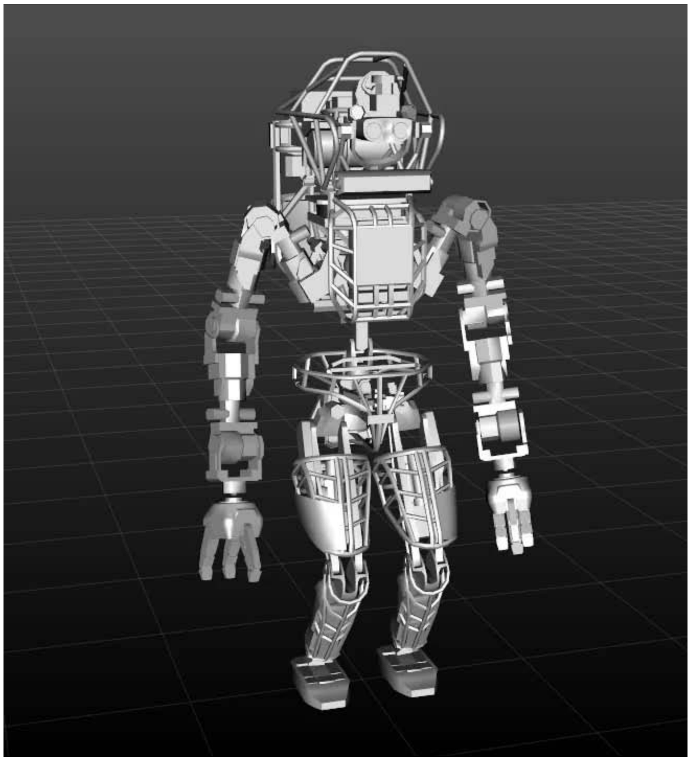
Our approach:

- Human provide high level knowledge / goals (using "affordances")
- Seeds (nearly) autonomous algorithms for perception, planning, control

Our technical approach

Almost everything the robot does is formulated as a mathematical **optimization**

Inverse Kinematics



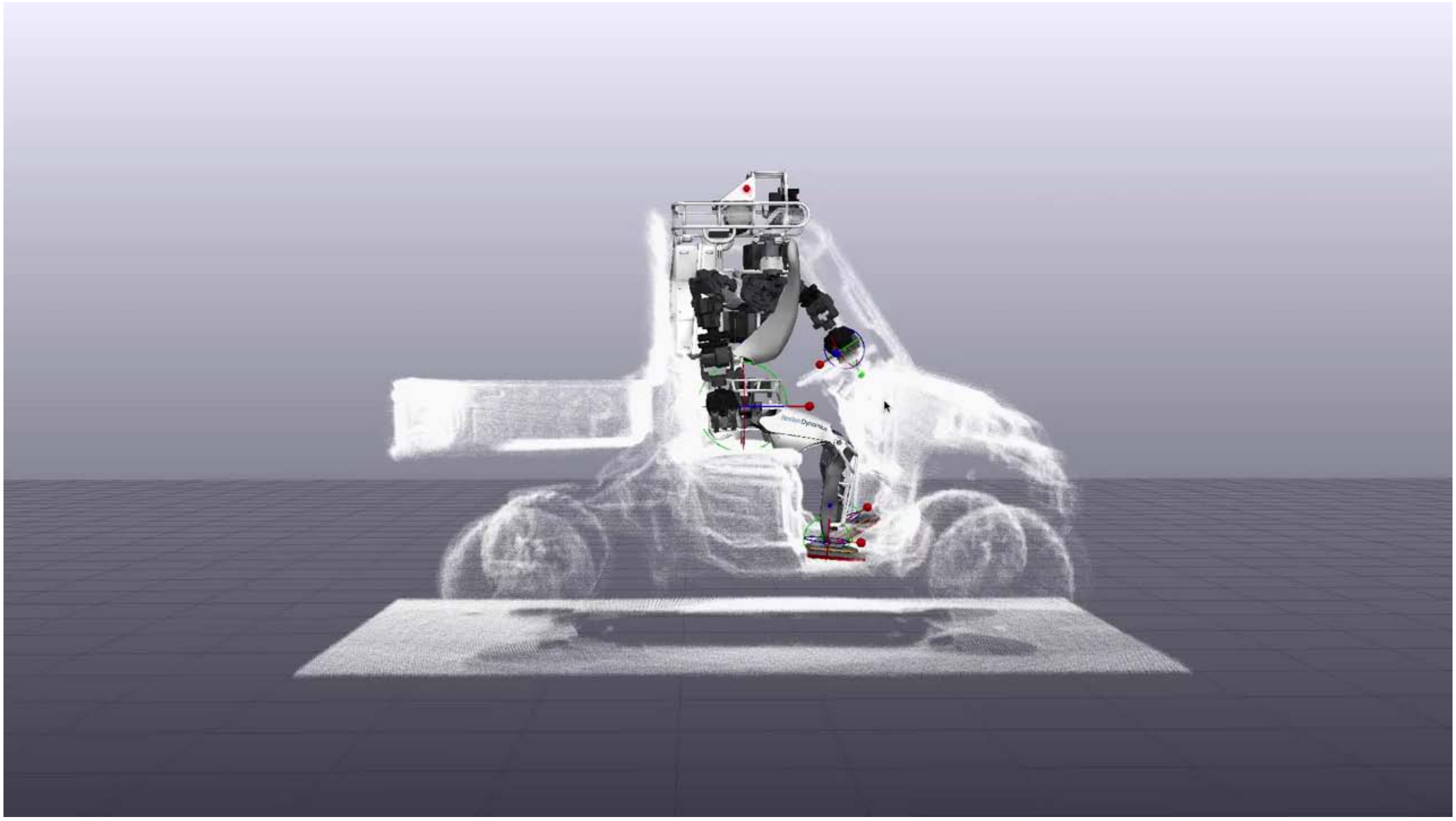
Joint positions: q

$$\min_q |q - q_{desired}|^2$$

subject to

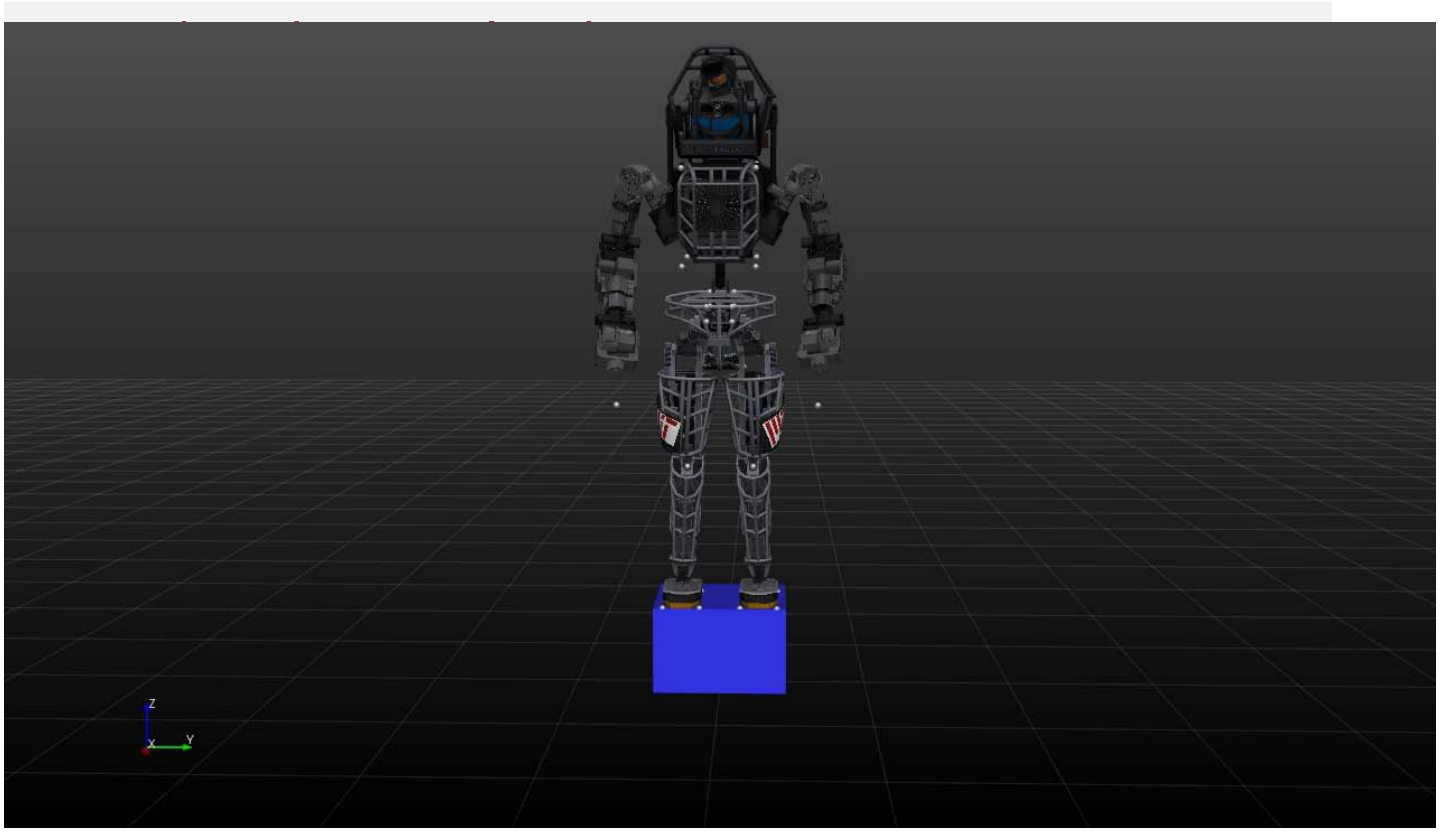
- end effector (rich constraint spec)
- joint limits
- collision avoidance
- "gaze constraints"
- feet stay put
- balance constraints (center of mass)
- ...

Big robot, little car



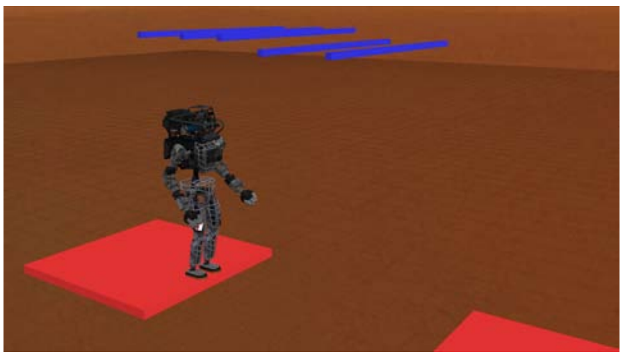
Research Nugget

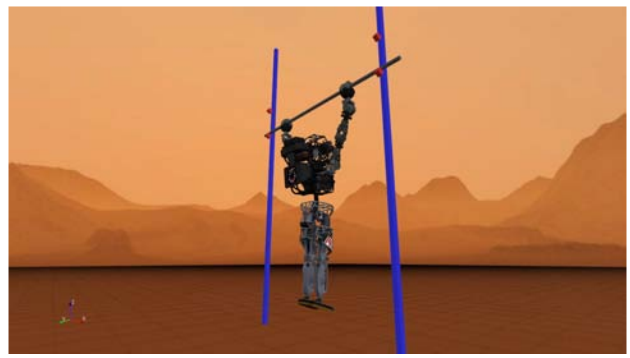
Efficient kinematic/**dynamic** motion planning for humanoids


Z
X
Y

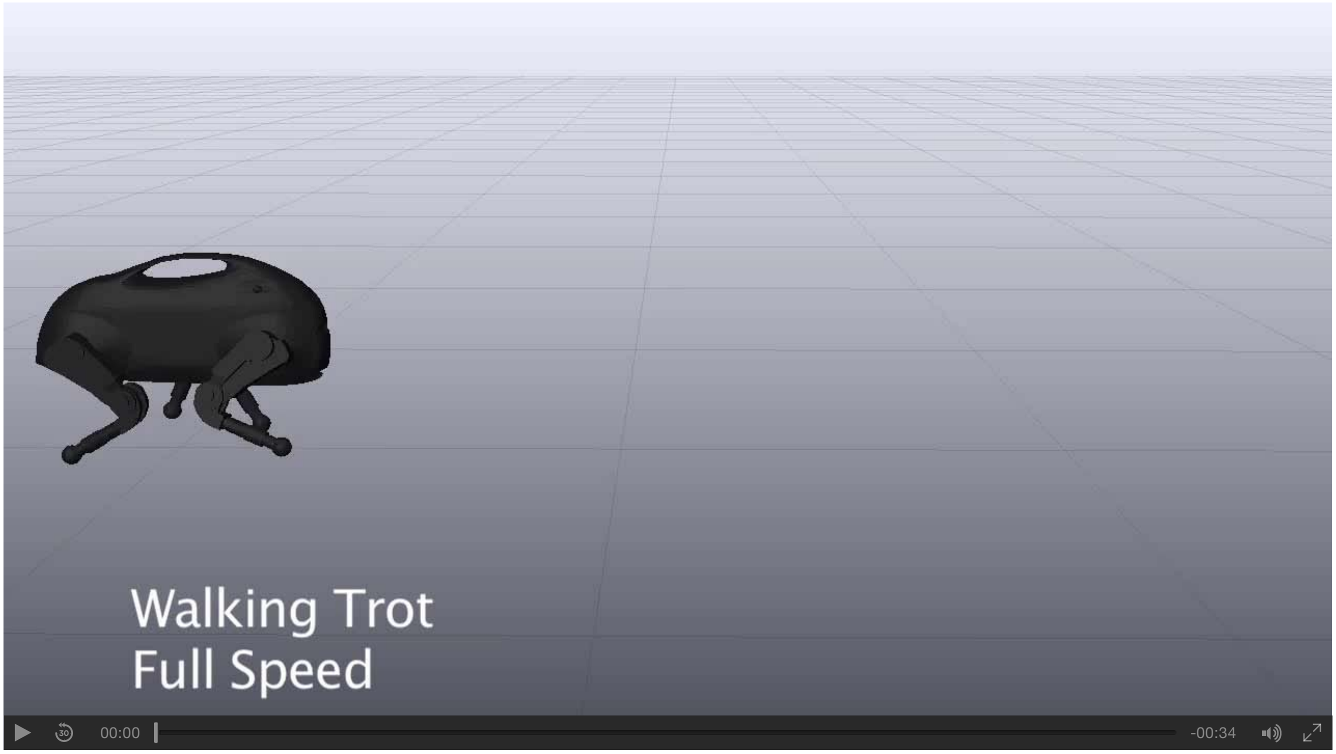
Dynamic trajectory planning

- Is there a way to generalize the insights from ASIMO/ZMP walking?
- **Key insight from ZMP:**
  Plan feasible contact forces / center of mass first, then fill in the details
- New algorithm uses:
  - 3D center of mass + centroidal momentum.
  - No actuator limits => all dynamic constraints in 6 dimensions.
  - Complementarity formulations for (frictional) collisions/impact.





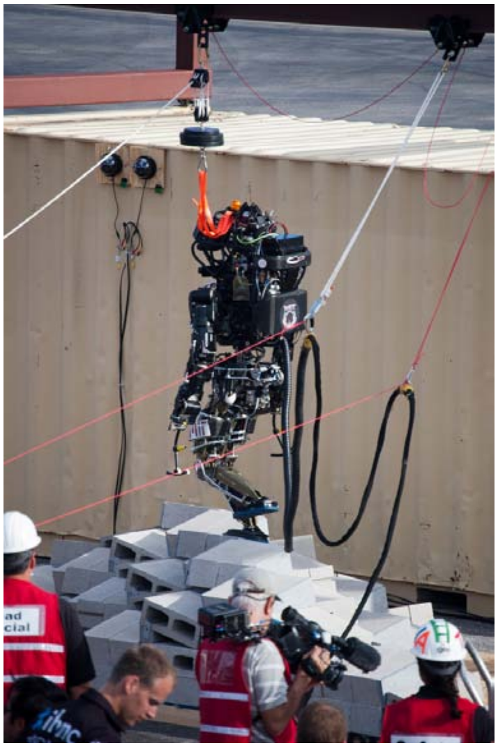
- Custom optimization-ready dynamics engine (analytical gradients, expose sparsity, ...)


Walking Trot
Full Speed
00:00
-00:34

Research Nugget

Combinatorial Footstep Planning

Footstep planning

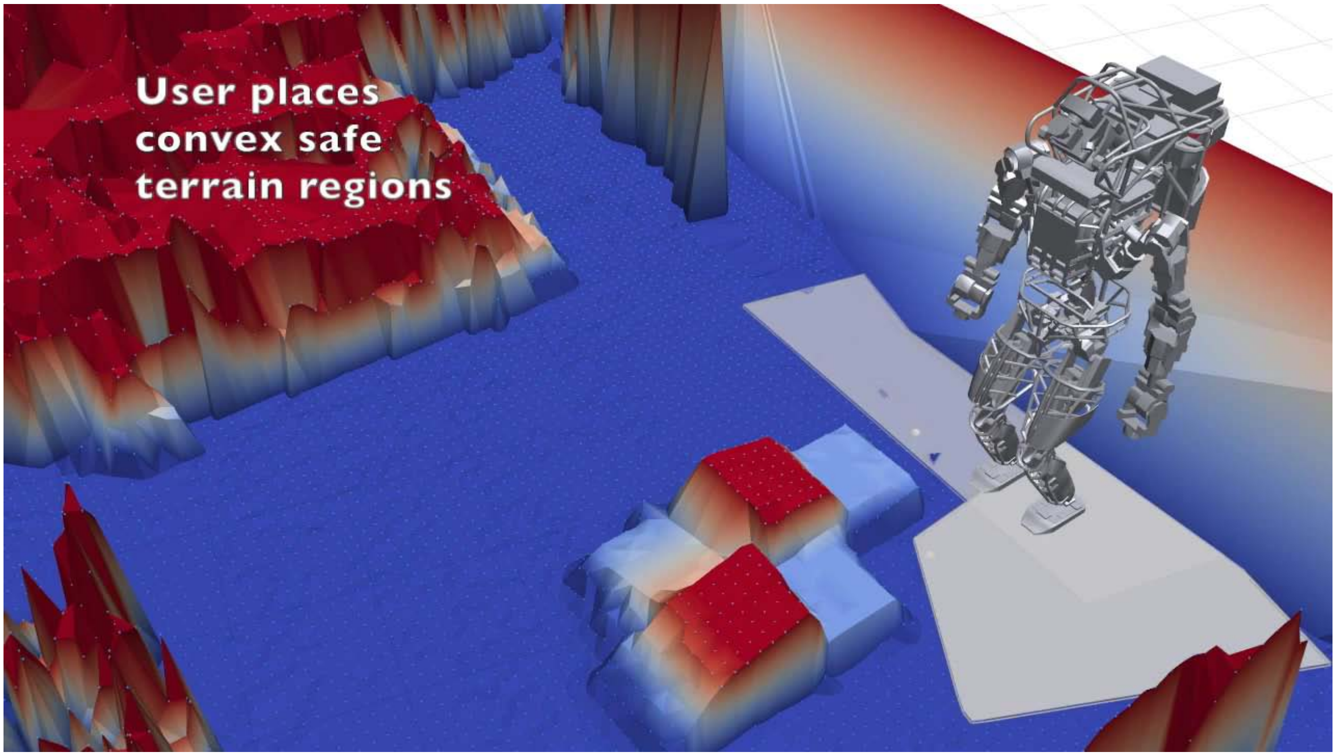


Trajectory optimization very efficient for local solutions.

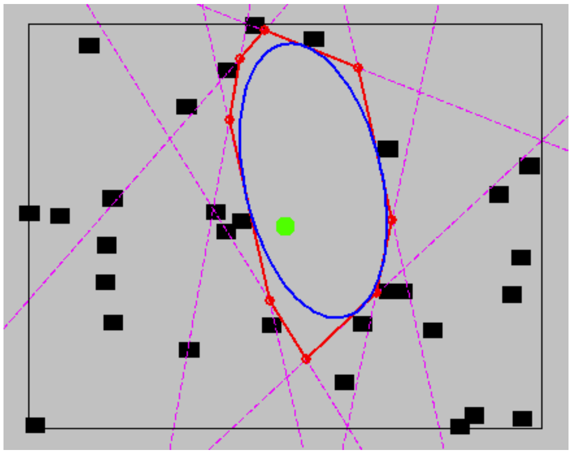
But there is still a combinatorial problem in walking:

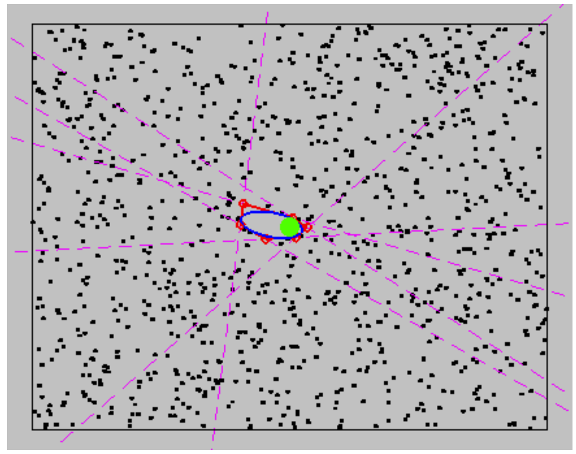
- Left foot or right foot?
- Cinderblock A or block B?

Developed new methods to explicitly expose combinatorial structure

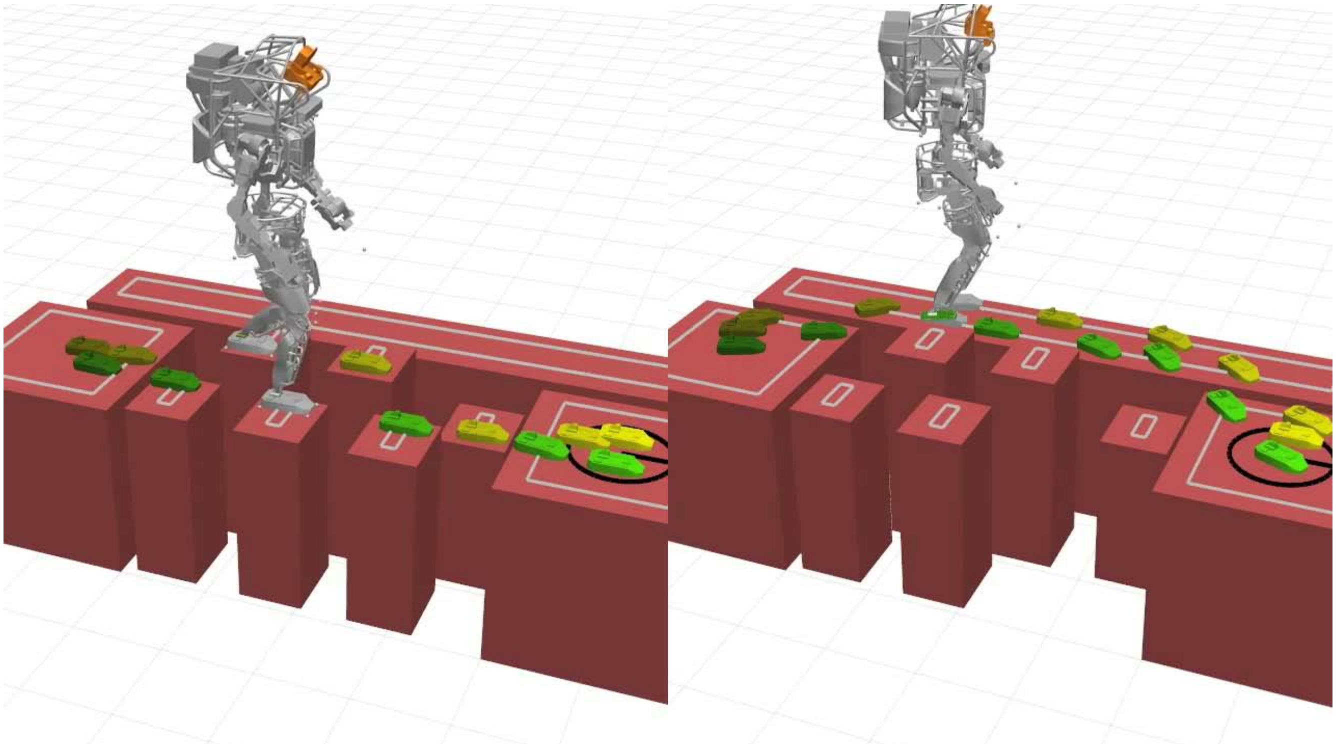

User places
convex safe
terrain regions

Super-fast approximate convex segmentation





- Iteration between (large-scale) quadratic program and (relatively compact) semi-definite program (SDP)
- Scales to high dimensions, millions of obstacles

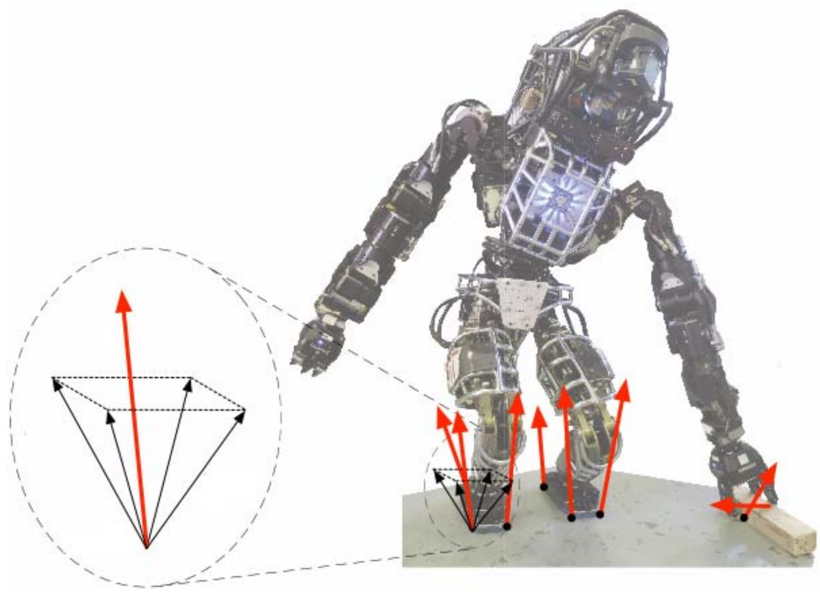


Research Nugget

Efficient optimization for multi-contact feedback control

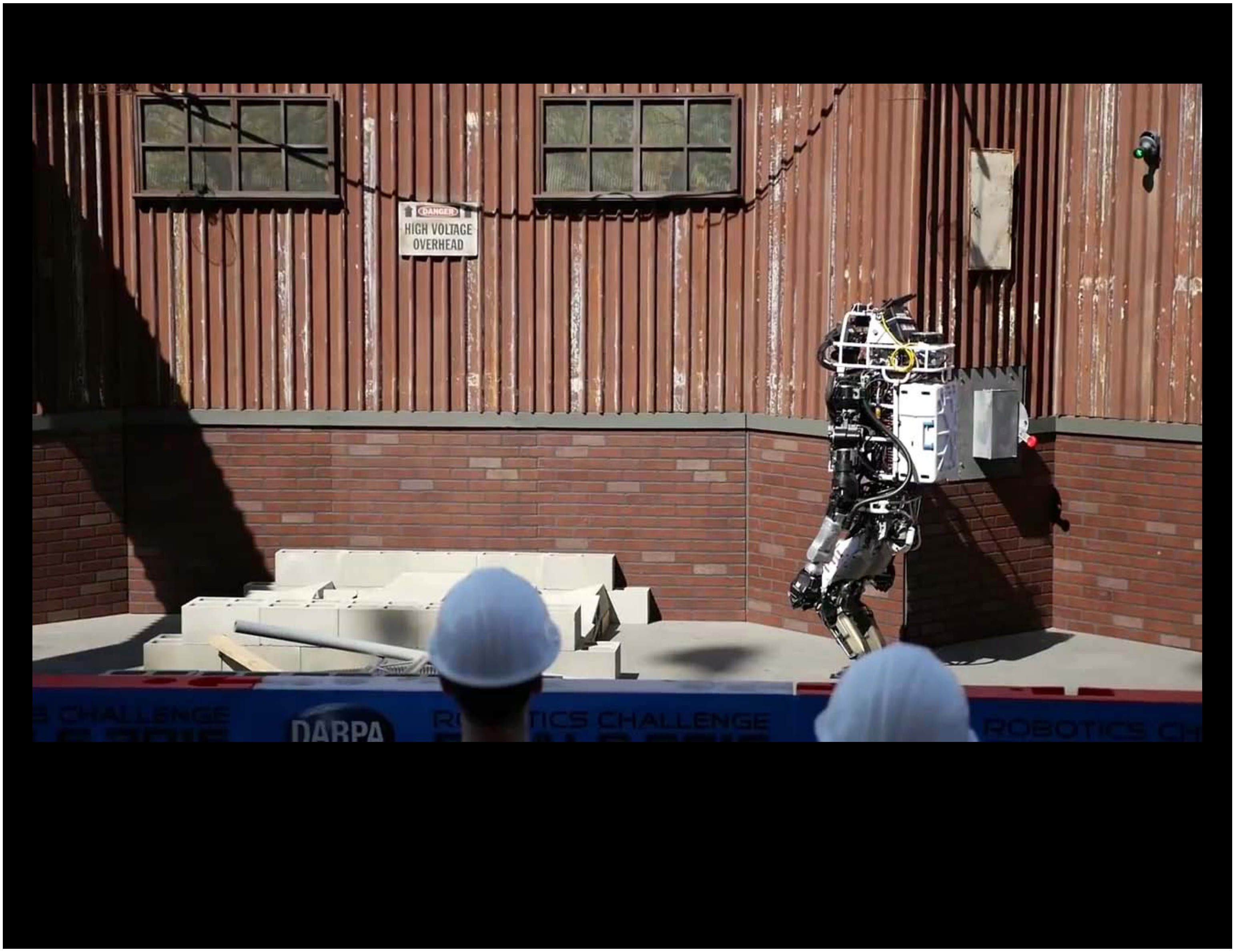
Quadratic Program for Whole-Body Force Control

- Explicit solution for least-squares regulation of *center of pressure trajectory*
- **Control-Lyapunov function** stability constraint + whole-body objectives
- One-step model-predictive control is a (sparse) quadratic program
- Custom active-set solver to achieve $>$ 1 kHz



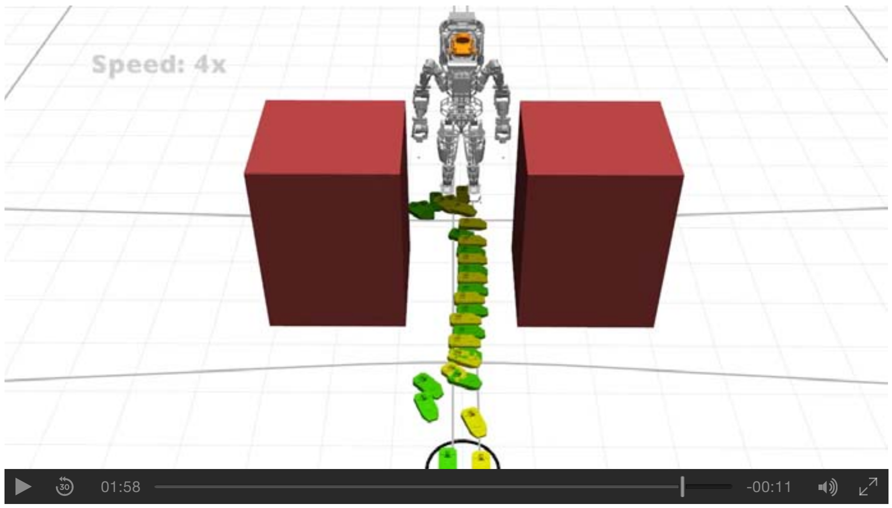
Basic Competency:

Walking and Balance


DANGER
HIGH VOLTAGE
OVERHEAD
DARPA

Walking Performance

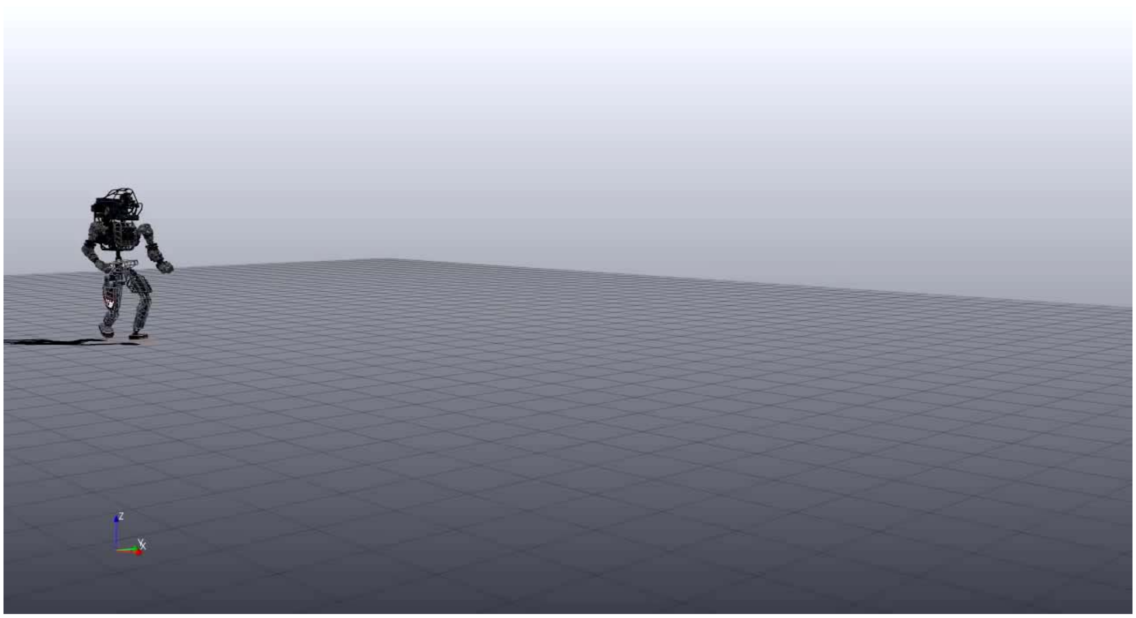
- For (mostly) flat foot, near constant center of mass height walking...
  - Planners work well (almost instantly) on simple to moderate terrain.



  - User interface let's human review / adjust footsteps.

Walking Performance (cont)

- More dynamic plans take ~1 minute to compute



- ...and don't always succeed (local minima, ...)

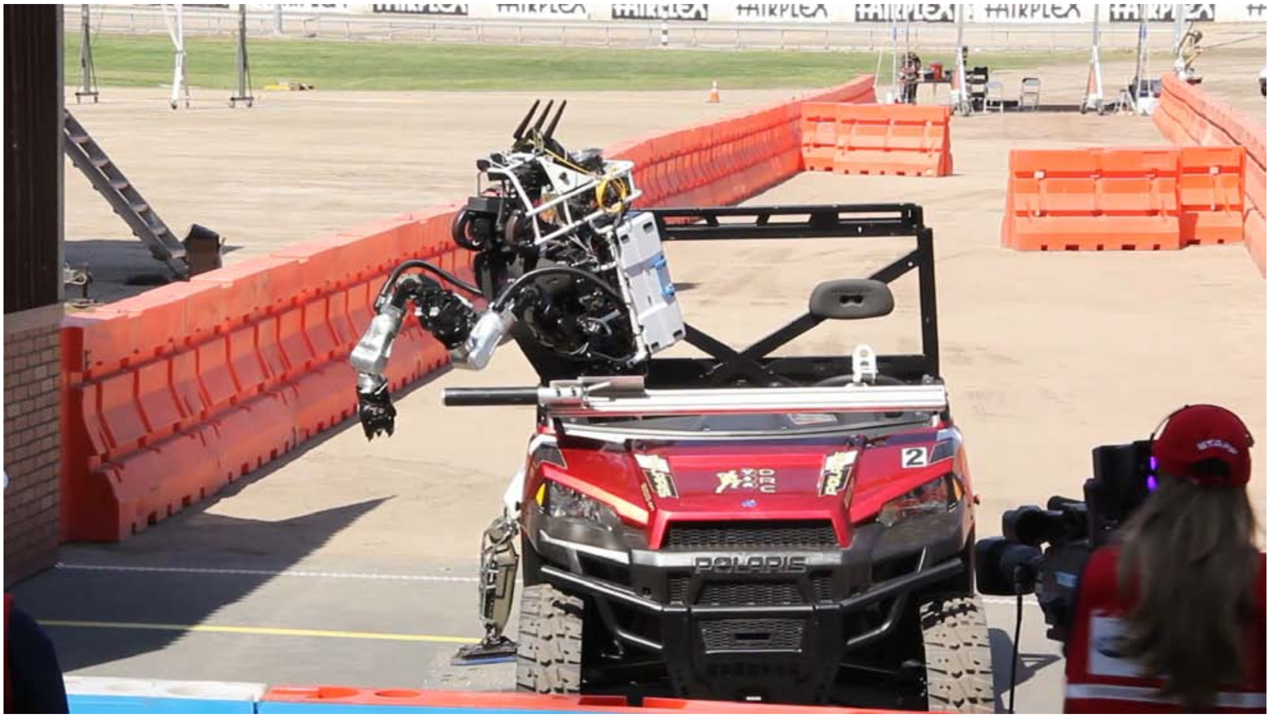
Walking Performance (cont)

- Balance control worked extremely well...


ihmcROBOTICS

Walking Performance (cont)

- Balance control worked extremely well...
- ... except for the one time it didn't



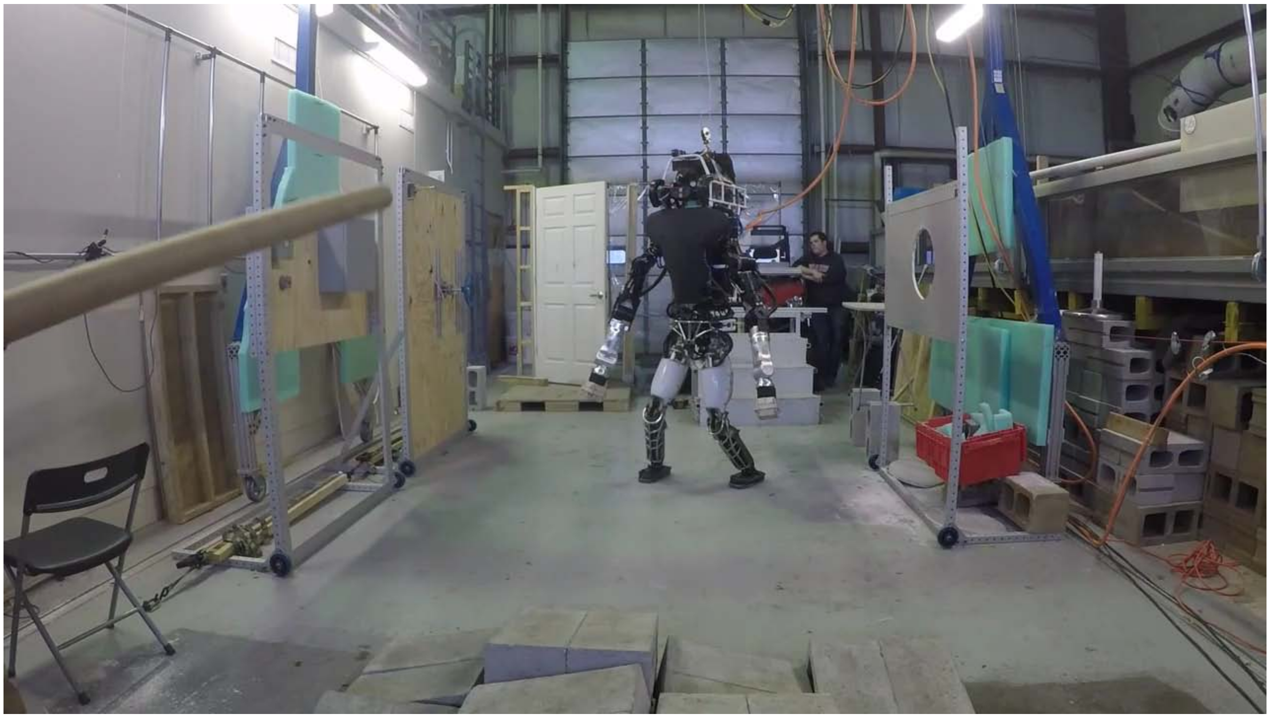
A Limitation Exposed

- Fundamentally based on planning (single trajectories) + "local" feedback.
  - When things are going (nearly) according to plan, very robust
  - But tailbone hit the seat and feet came off the ground...
    - No contact sensor in the butt
    - Dynamics model very wrong
    - State estimator very confused
    - Controller is hosed!
  - Still susceptible to big deviations from the nominal plan

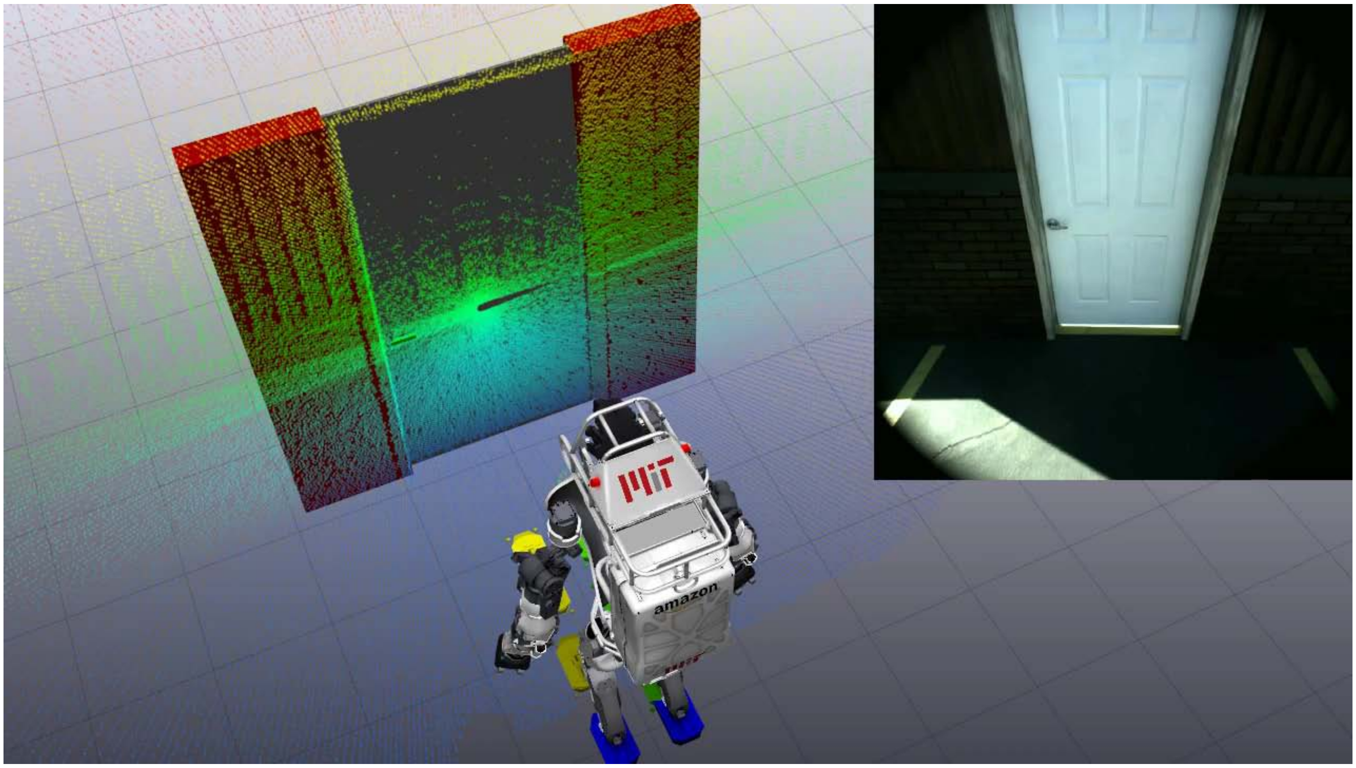
- A few ways to address it
  - All fundamentally about ***robustness***
  - (More on this in a minute...)

Ironically

- For flat terrain, we did work out good heuristics...



Another form of robustness

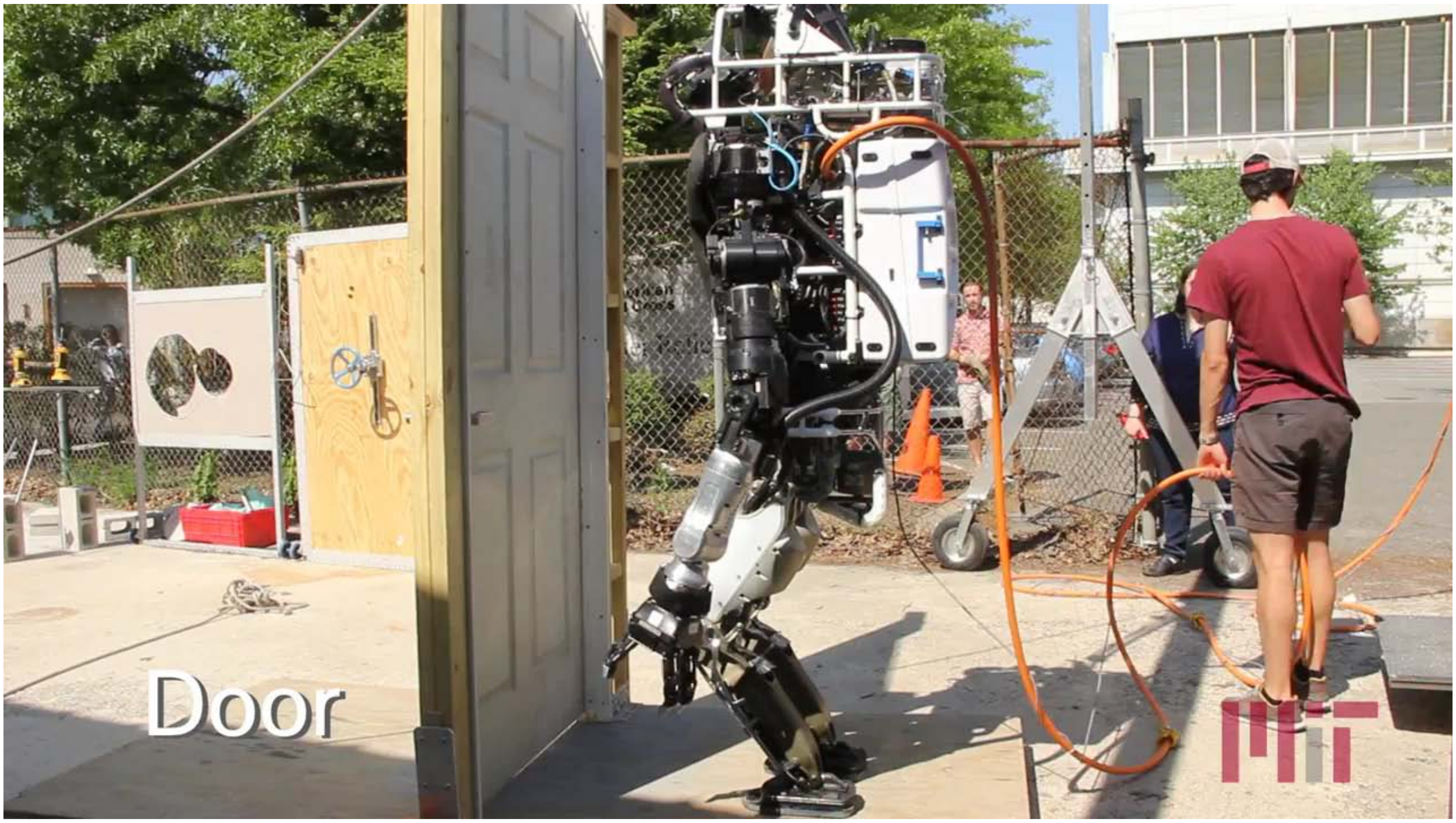


Basic Competency:

Manipulation

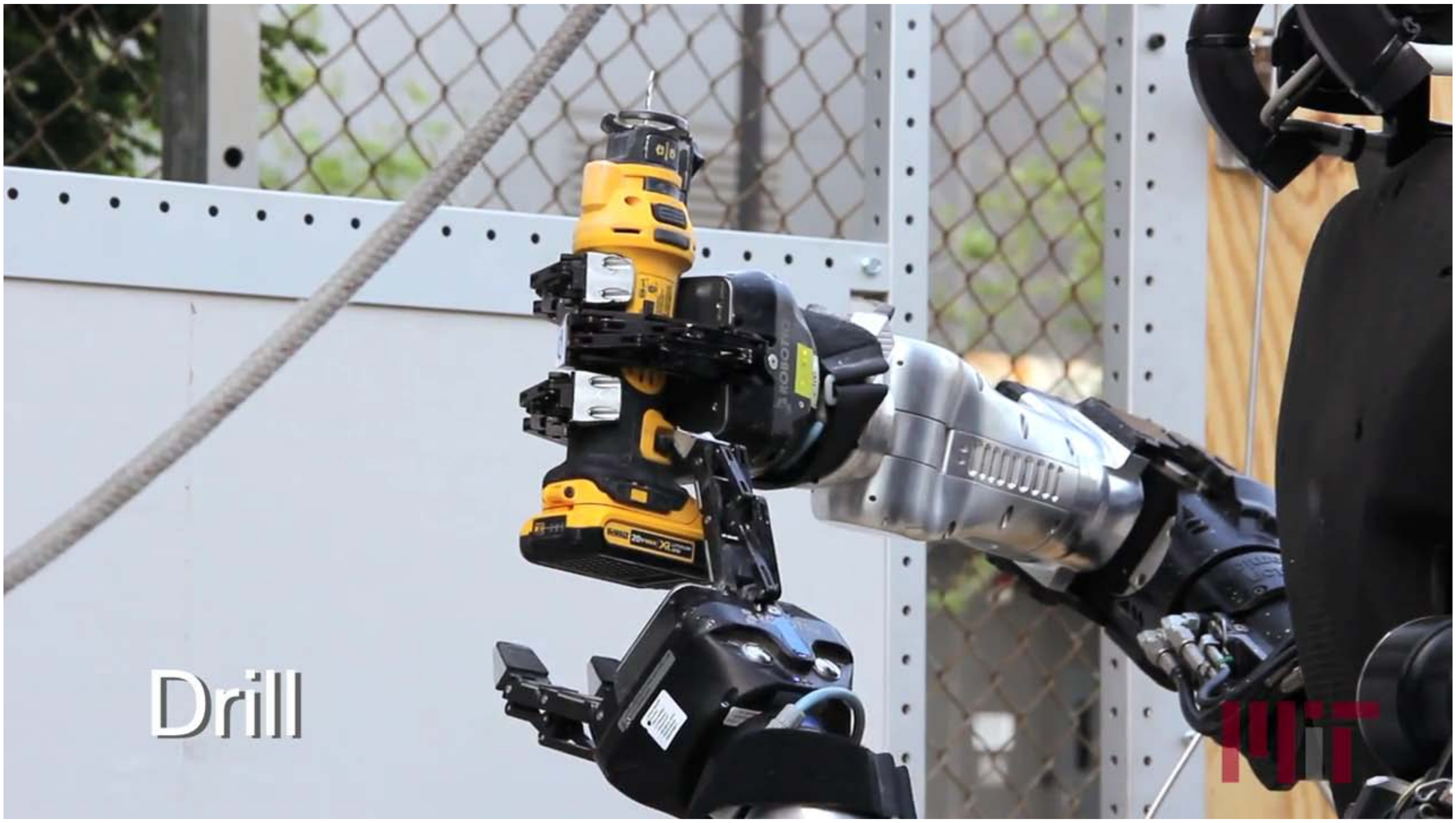
Manipulation Performance

- Only basic manipulation was required



Manipulation Performance

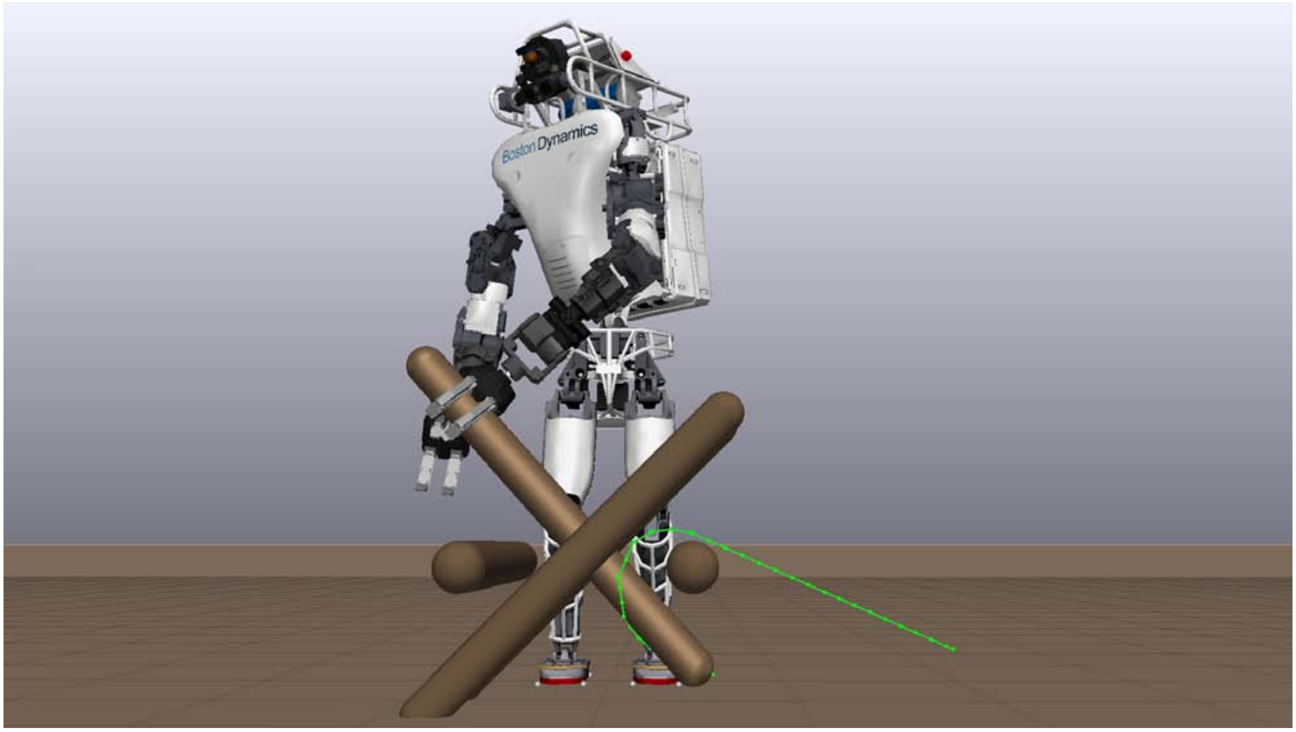
- Only basic manipulation was required



Manipulation Performance (cont)

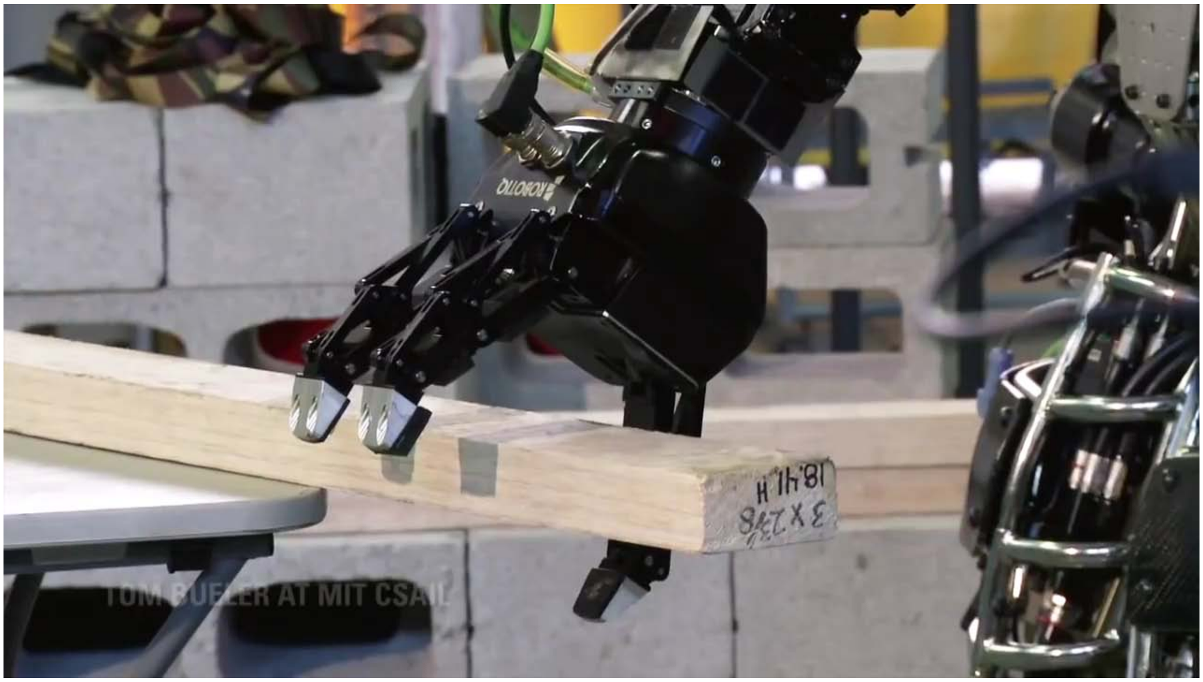
- Again, planning worked very well

Manipulation Performance (cont)



Manipulation Performance (cont)

- But grasping was open-loop (no feedback)



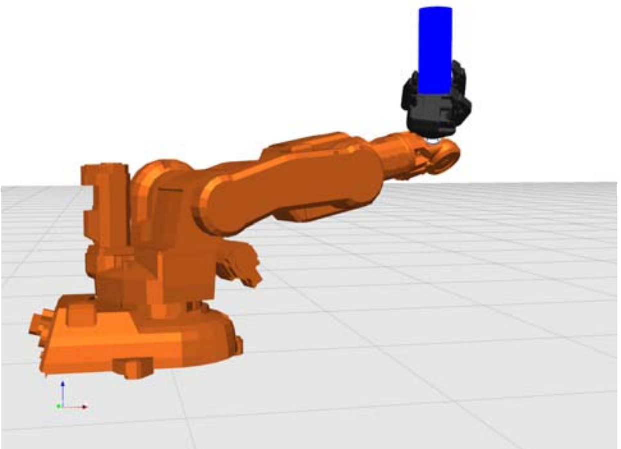
- Touch sensors / hand cameras were fragile and difficult to use

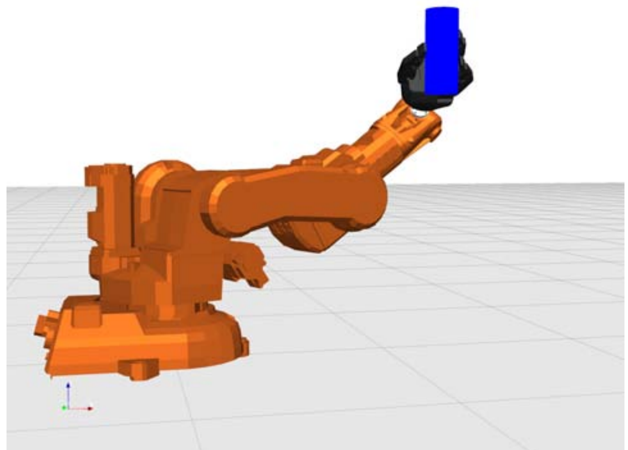
Research Nugget

Grasp Optimization using Convex Optimization

Grasp optimization

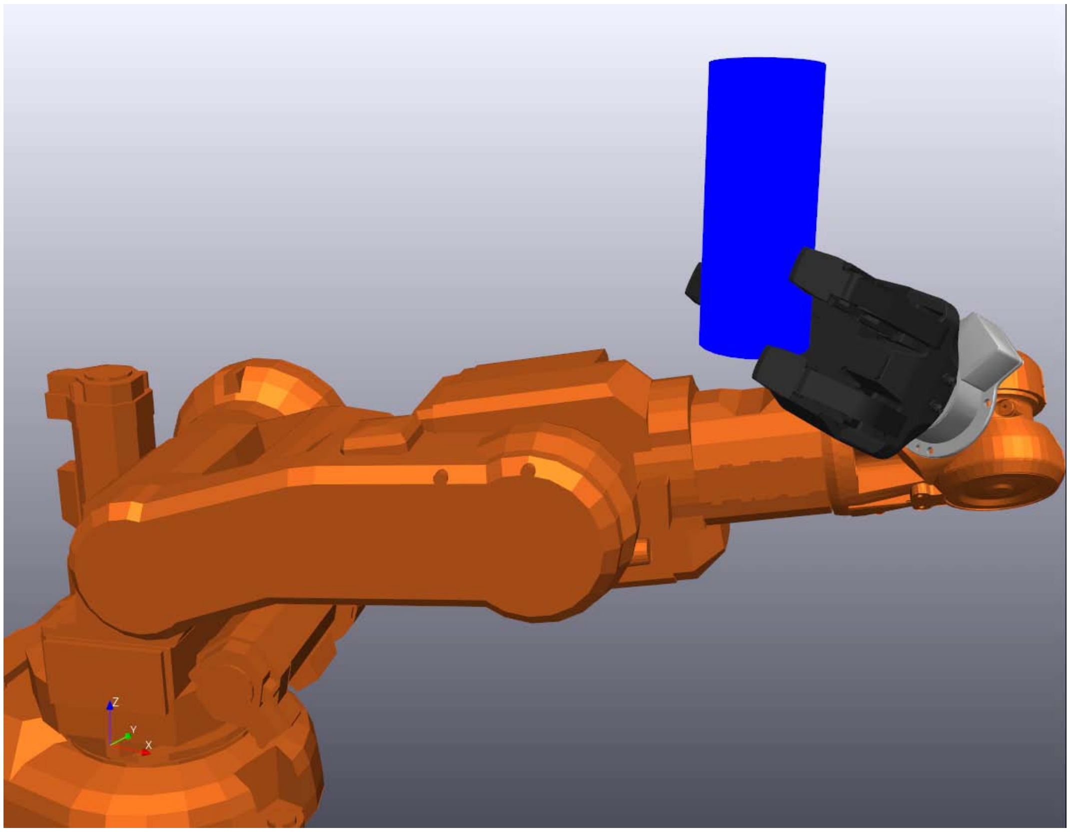
- Optimize forces *and* **contact positions** for robustness
- Bilinear Matrix Inequalities (solved as SDP w/ rank-minimization)
- Include kinematic and dynamic constraints (solves inverse kinematics, too)





Grasp optimization

- Find pose to maximize wrench disturbance given torque limits

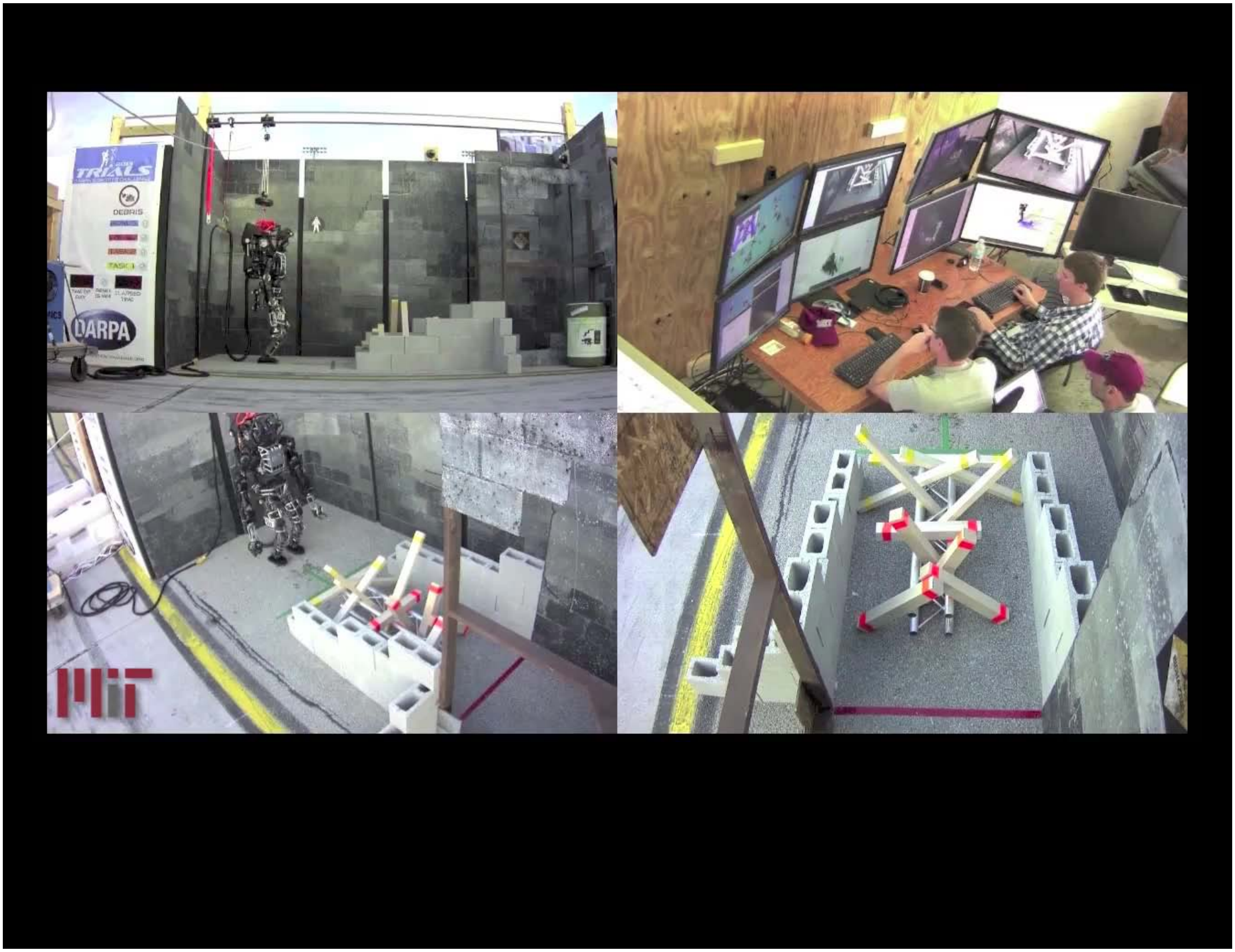


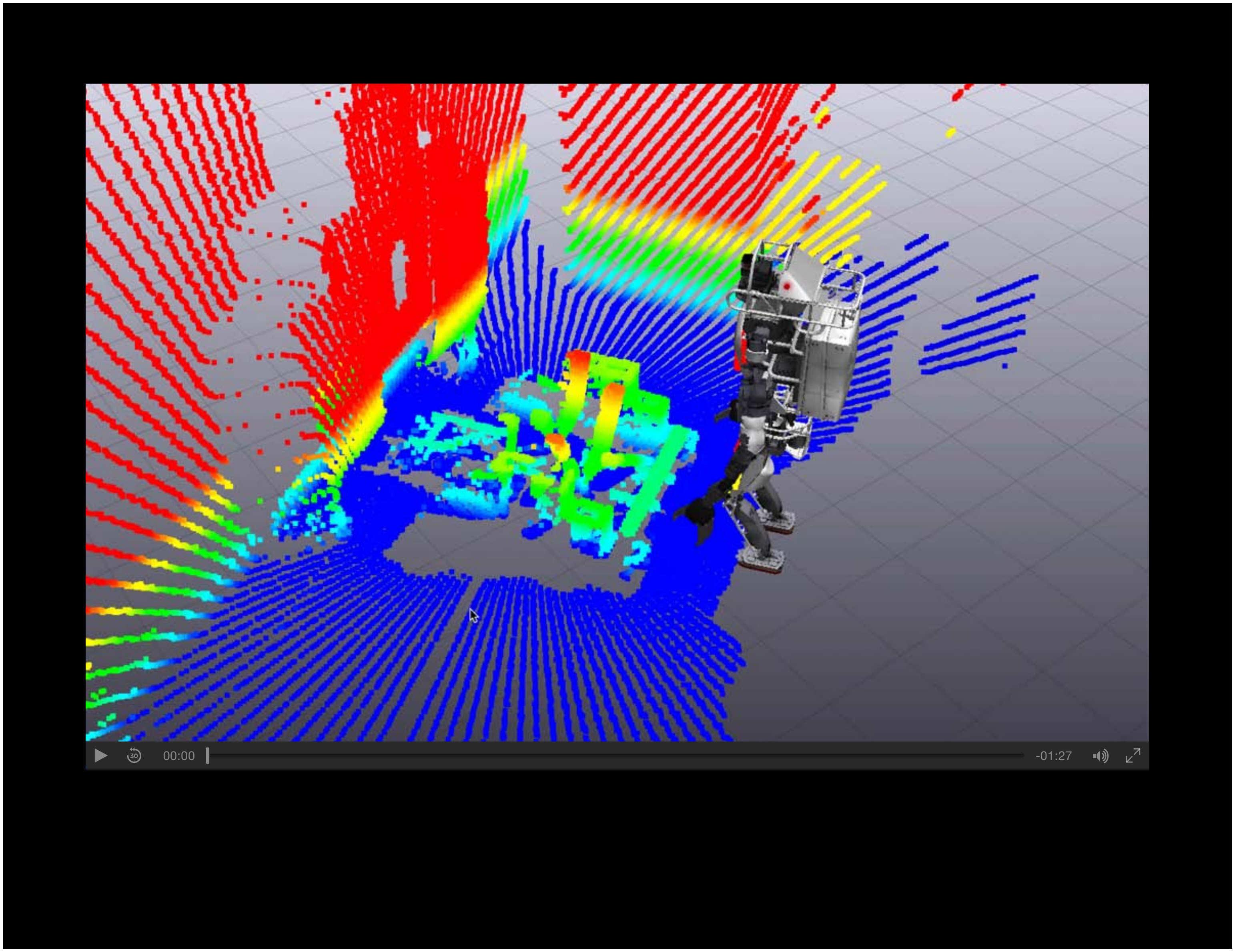
Research Nugget

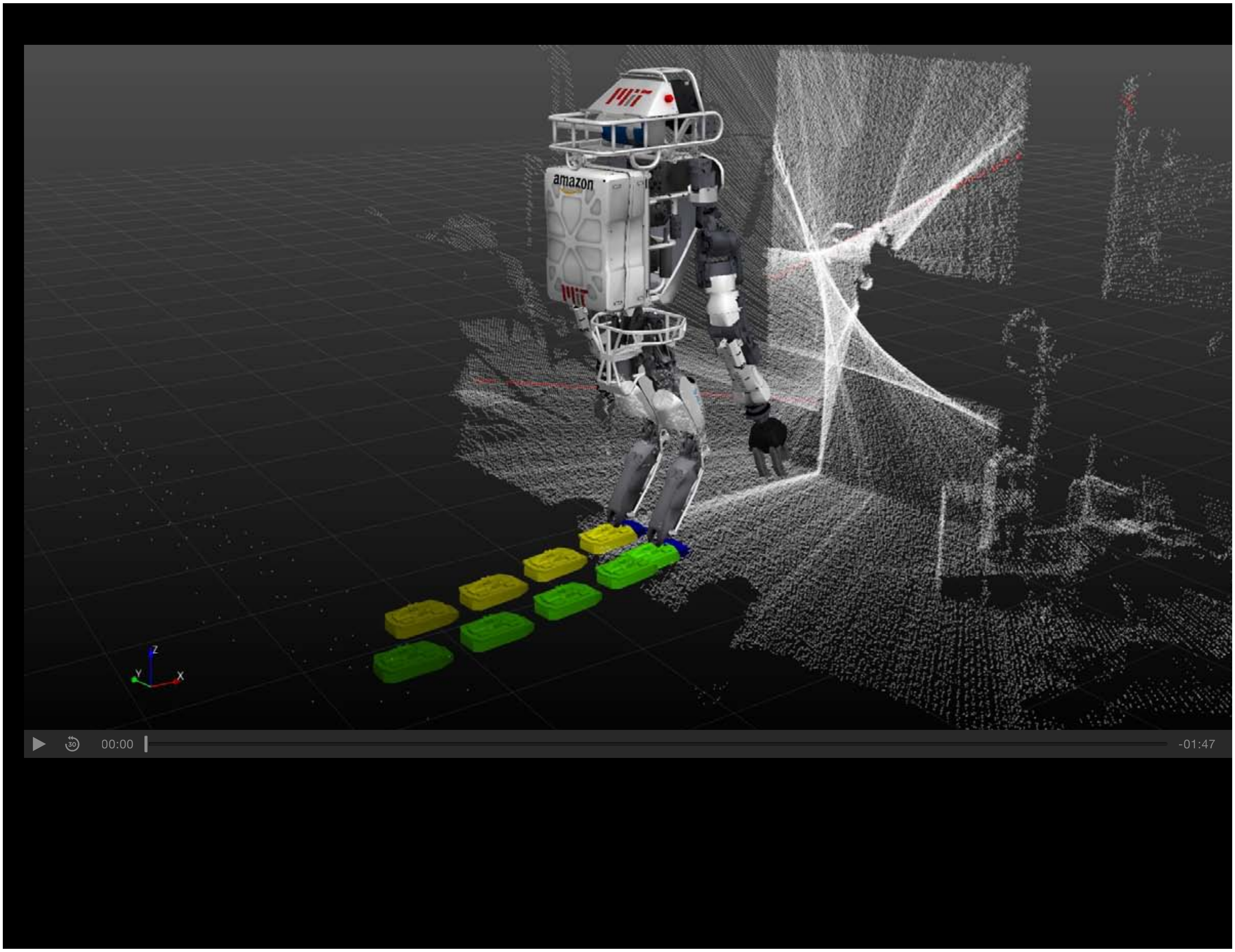
Perception algorithms aided by minimal user interaction

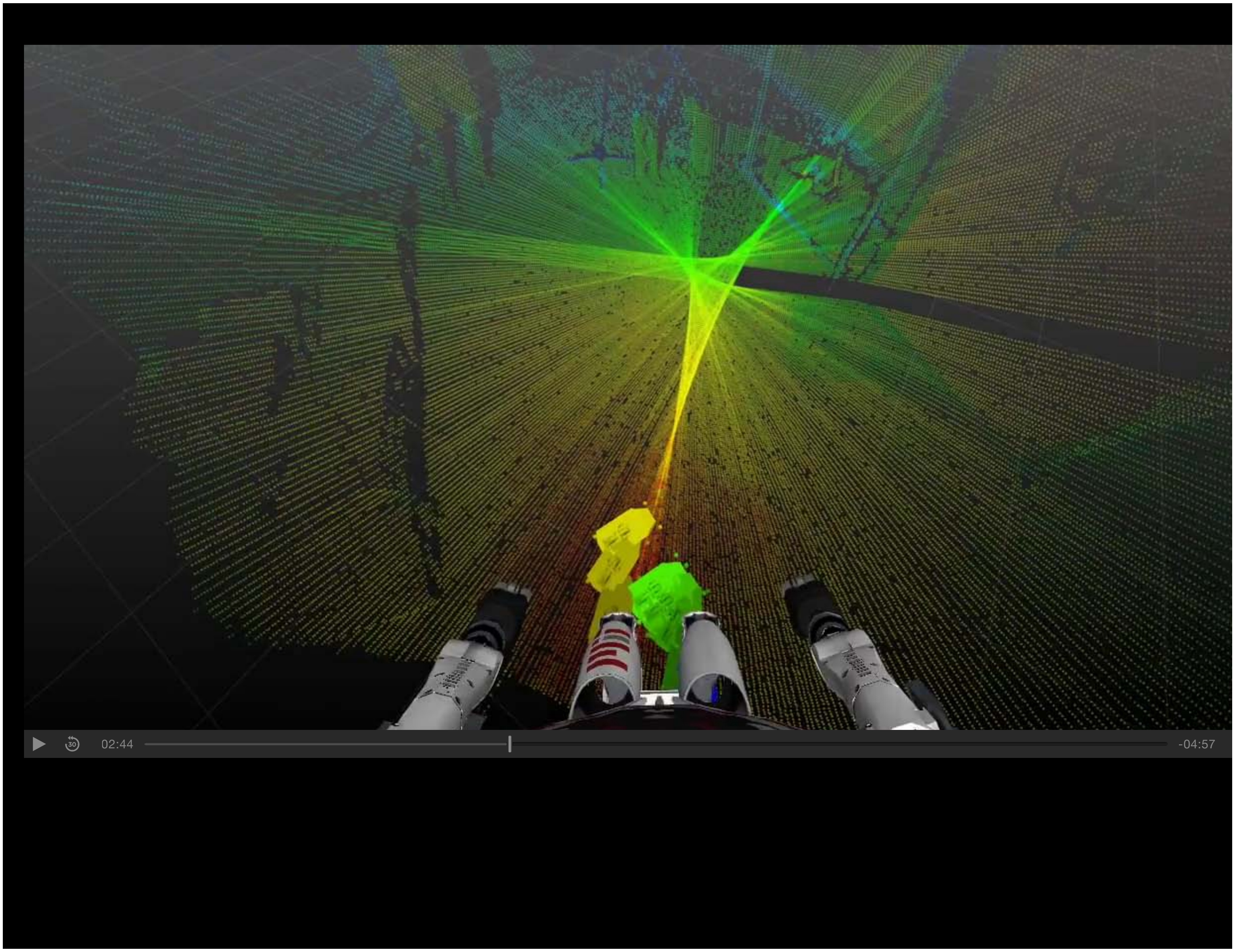
Task 3: Remove Debris Blocking Entry
2.2 kg (5 lb) and 4.4 kg (10 lb) Debris

The stage shown (grey) is 4.8 m (16 ft) wide x 3.6 m (12 ft) deep x 3.0 m (10 ft) tall with a central alcove for the robot to enter that is 80 cm (32 in) wide x 2.1 m (7 ft) tall blocked with well defined debris in a describable arrangement. The entry has partial cinder block walls on both sides to contain the debris and ensure all robots approach the pile similarly. This task encourages grasping, lifting, and placing enough debris over the side of the partial walls to pass through the entry.


TRIALS
DEBRIS
TASK 1
DARPA


00:00
-01:27


amazon
00:00
-01:47


02:44
-04:57

Why were the robots often standing still?

- Not waiting for human.
- Not planning time.
- Mostly waiting for lidar.

Research Nugget

(Continuous) walking with dense stereo and *drift-free* state estimation)


4x
00:00
-03:01

The tip of the iceberg

- Networking...
- Systems...
- Build servers, unit tests, ...
- Logistics...
- Politics...

Reflections

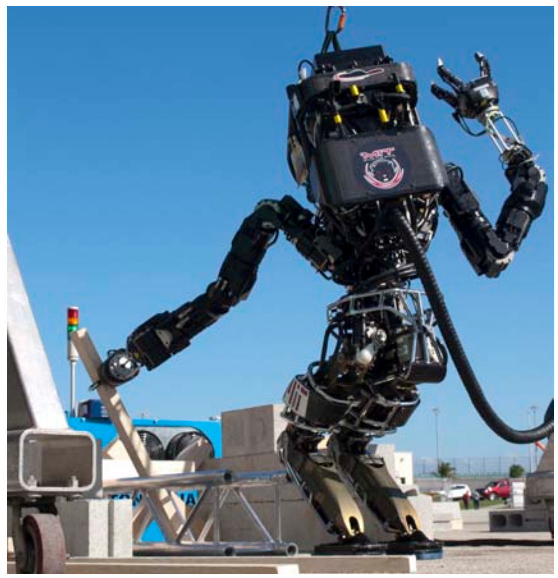
- We gave it everything, but didn't win the competition
- Huge success overall!
  - Robots could move faster with only small changes (mostly perception)
  - Walking was sufficient; can make it much better
  - Basic but capable manipulation
  - Robustness (e.g., fear of falling) a constant dominating concern
- Incredible software tools for future research

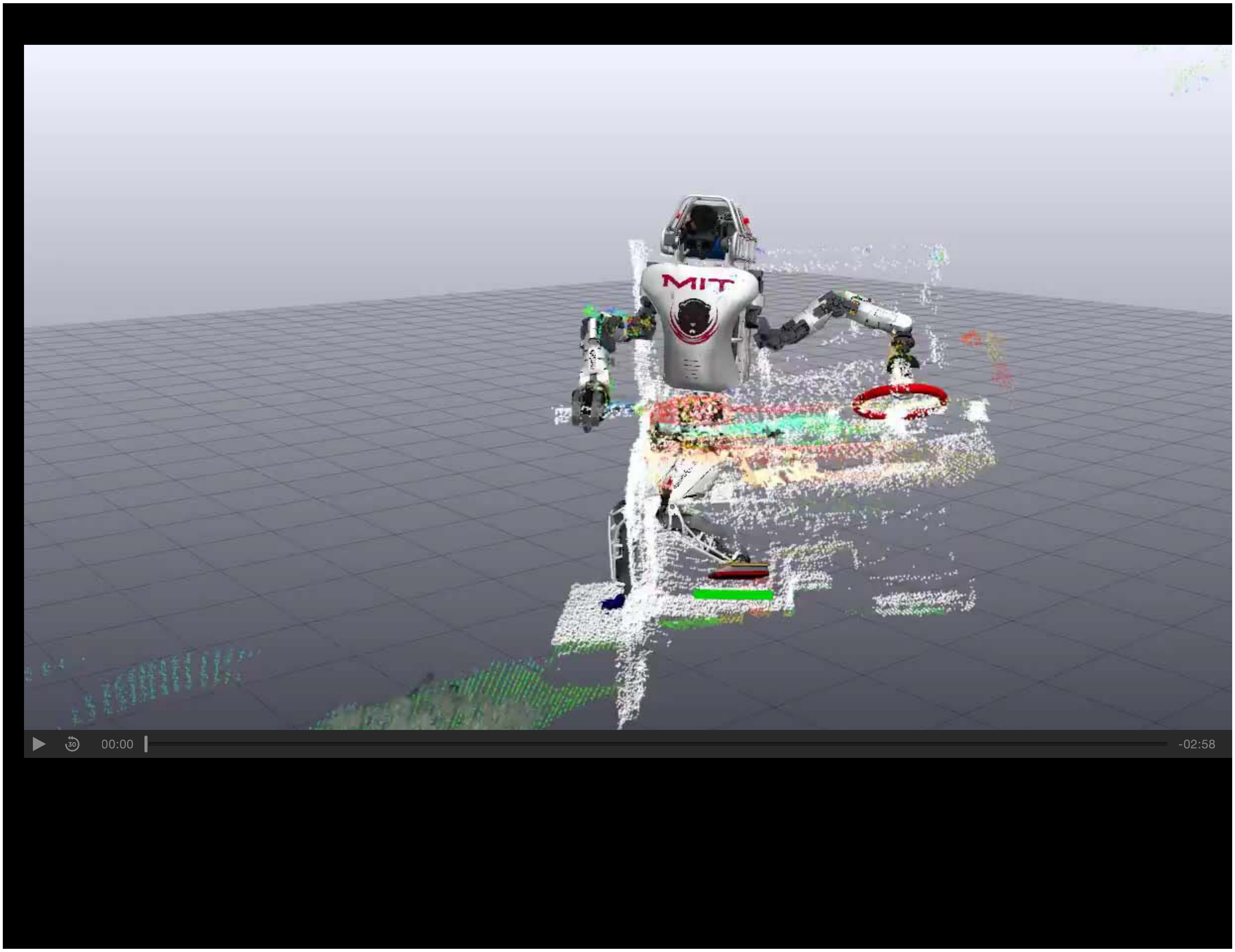
- I think the most important problem is...
  - Achieving *robustness* despite *model errors* and changing *contact* conditions
  - Shouldn't be afraid to make contact (anywhere on the body)
  - Lots of immediate applications (e.g. in *manipulation*)

Image removed due to copyright restrictions. Please see the video.

For more information

- Papers available at: http://groups.csail.mit.edu/locomotion/
- Software all open on github (shortcut: http://drake.mit.edu)
- Online course (edX) this fall: http://tiny.cc/mitx-underactuated
- Get involved with Robotics@MIT




MIT
00:00
-02:58