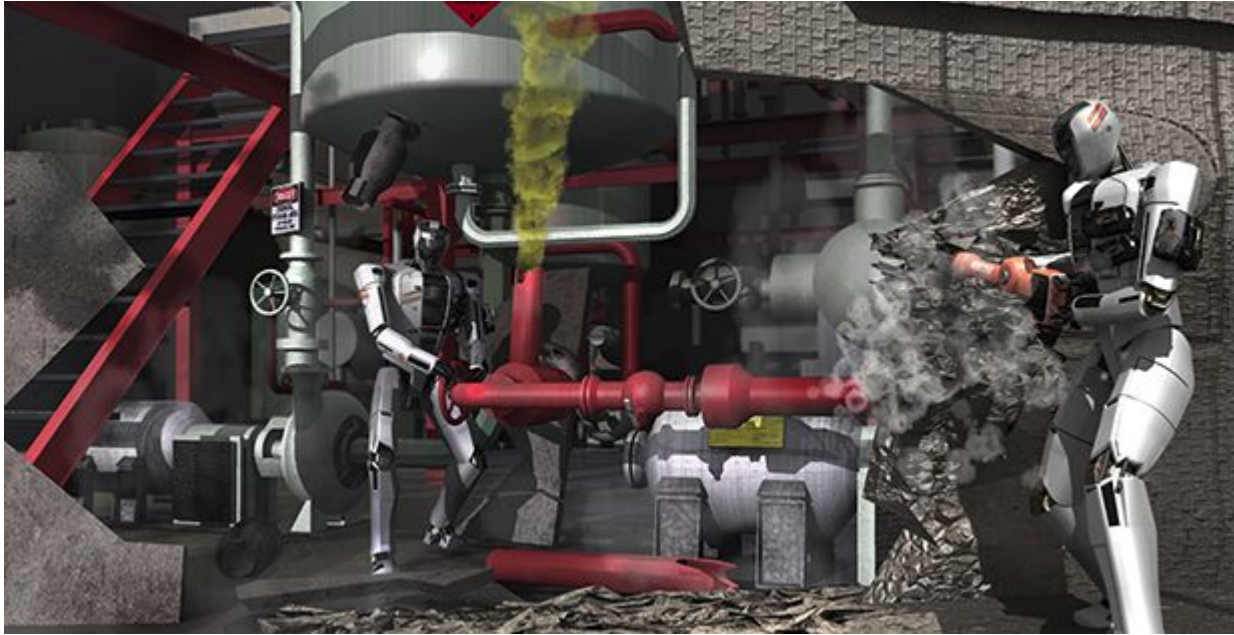


Full-body motion planning and control for the egress task of the DARPA Robotics Challenge

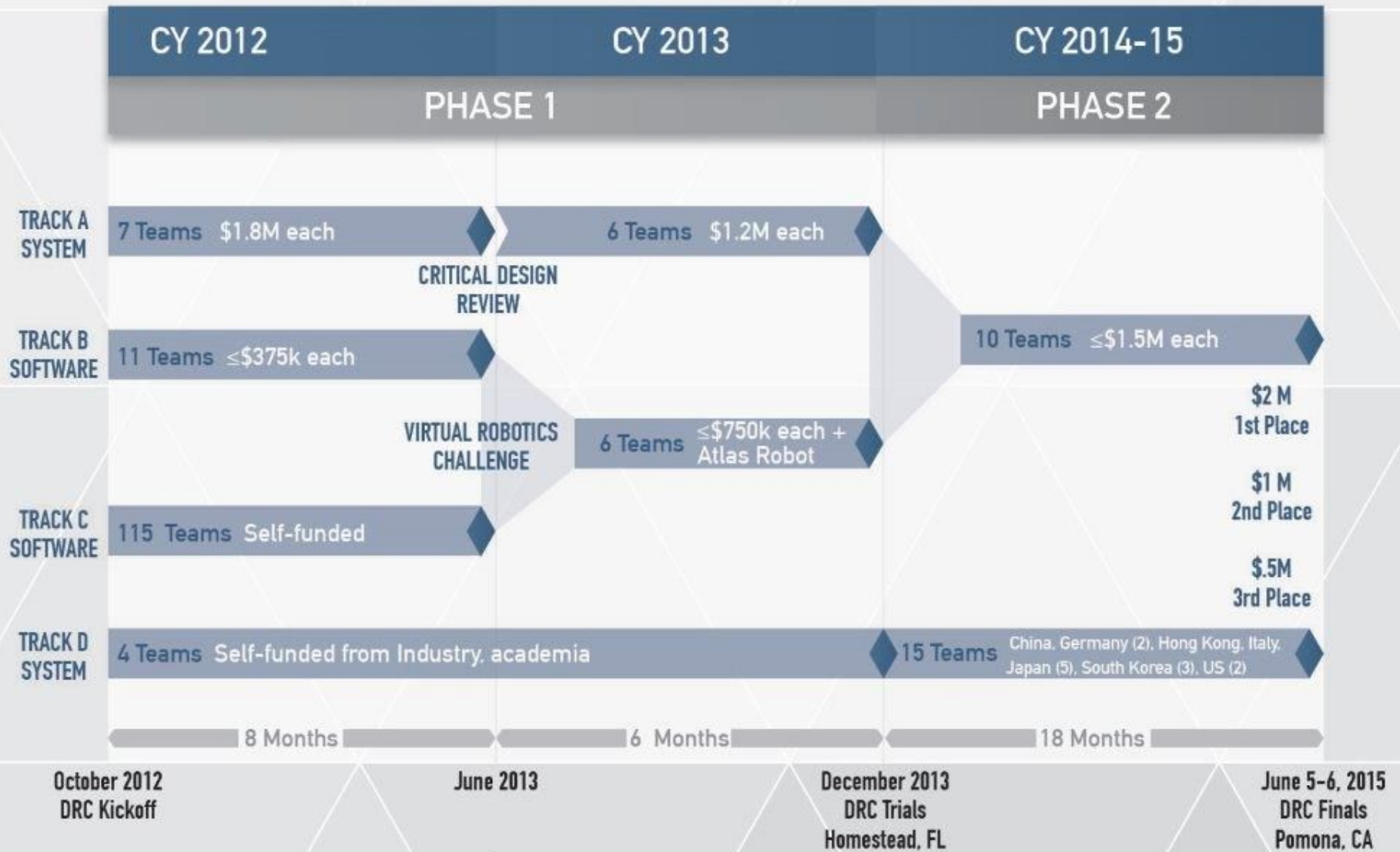
Outline

- DARPA Robotics Challenge
 - Program structure, funding, and teams
 - Tasks and rules
- Egress Task
 - Rules
 - Challenges
- Our approach
 - Offline discrete contact and waypoints optimization
 - Online pose optimization and control
- Software implementation
- Results



The primary technical goal of the DRC is to develop human-supervised ground robots capable of executing complex tasks in dangerous, degraded, human-engineered environments. Competitors in the DRC are developing robots that can utilize standard tools and equipment commonly available in human environments, ranging from hand tools to vehicles.

DRC PROGRAM STRUCTURE + FUNDING



THE DARPA ROBOTICS CHALLENGE FINALS

AN INTERNATIONAL COMPETITION

United States

Team Tartan Rescue
Team DRC-Hubo
Team Grit
Team IHMC Robotics

Team MIT
Team RoboSimian
Team THOR
Team TRACLabs

Team Trooper
Team VALOR
Team ViGIR
Team WPI-CMU

South Korea

Team KAIST
Team ROBOTIS
Team SNU

Japan

Team Aero
Team AIST-NEDO
Team HRP2-Tokyo
Team NEDO-Hydra
Team NEDO-JSK

European Union

GERMANY
Team Hector
Team NimRo Rescue

ITALY
Team WALK-MAN

Hong Kong

Team HKU

DRC Finals 25



Hercules
(Team TRAC Labs)



LEO
(Team TROOPER)



Helios (Atlas)
(Team MIT)



Florian
(Team ViGIR)



THORMANG
(Team ROBOTIS)



THORMANG
(Team SNU)



THOR-RD
(Team THOR)



Johnny 05
(TEAM HECTOR)



Running Man
(Team IHMC Robotics)



Atlas
(TEAM HKU)



WARNER
(Team WPI-CMU)



Momaro
(Team NimbRo Rescue)



Aero DRC
(TEAM AERO)



Xing Tian
(Team Intelligent Pioneer)



DRC-HUBO
(Team KAIST)



DRC-Hubo
(TEAM DRC-HUBO AT UNLV)



HRP2+
(TEAM AIST-NEDO)



HRP-2
(Team HRP2-Tokyo)



RoboSimian
(Team RoboSimian)



Cog-Burn
(TEAM GRIT)



CHIMP
(TARTAN RESCUE)



WALK-MAN
(Team WALK-MAN)



ESCHER
(Team VALOR)



JAXON
(Team NEDO-JSK)



Hydra
(Team NEDO-Hydra)

<http://www.theroboticschallenge.org/teams>

Dropped drill due to bug



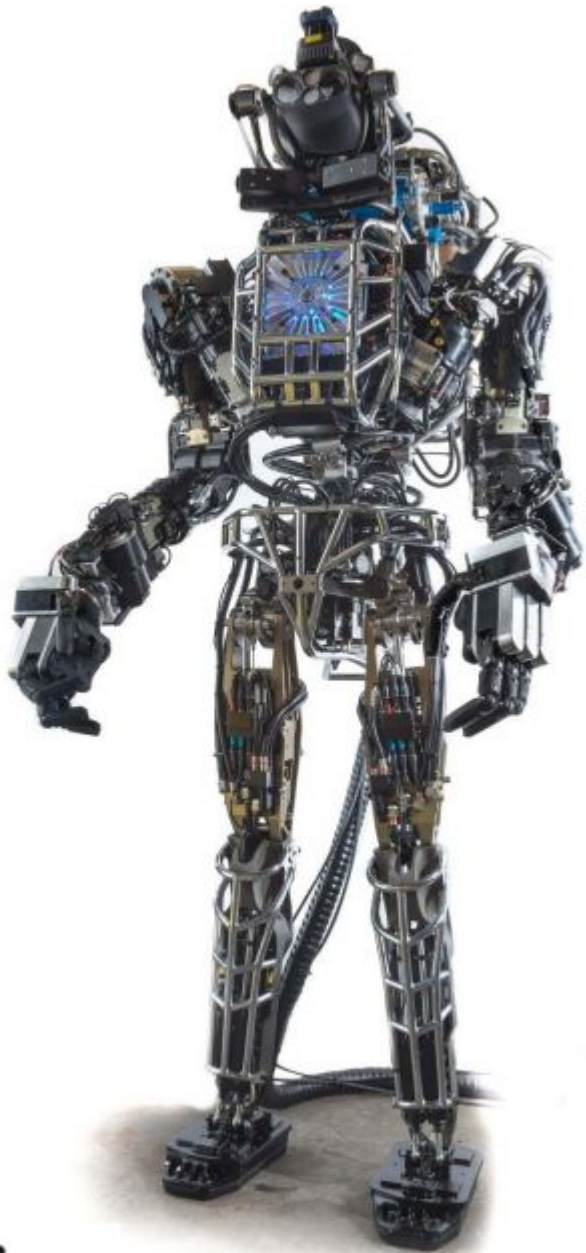
DRC Final Task 2 - Egress



Teams may also omit the Task 2 (Egress) by requesting a Reset at the end of Task 1 (drive). Once the Request has been granted, the Field team can manually remove the robot from the vehicle and place it in the Reset zone. Ten minutes must elapse before resuming the run, and no egress task point is awarded.

Rule:

- After getting out of the car, the robot must locomote to a task completion area marked on the pavement in front of the door.
- the center of mass of the robot (with on accessories) must do task 1 and start task 2 inside the unmodified vehicle. A practical test is the robot may passively stay in the unmodified vehicle when all hands and grips and attachments are release



- Near-human anthropometry
- 2 arms, 2 legs, torso and head.
- 28 hydraulically-actuated high-performance joints with closed-loop position & force control
- On-board real time control computer
- Electric power & network tether
- Crash protection
- Modular wrists accept 3rd party hands
- Head-mounted sensor package with LIDAR, stereo cameras, dedicated sensor electronics and perception algorithms.

Size:

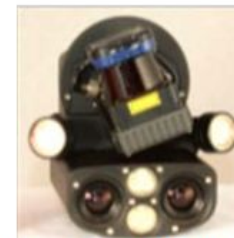
Weight: 330 lbs (150 kg)
Height: 74" (1.88 m)
Chest Depth: 22" (0.56 m)
Shoulder Width: 30" (0.76 m)

Required Power

480V 3-phase at 15 kW

Interface

10 Gbps Fiber Optic Ethernet
C++ and ROS APIs



Carnegie Robotics
Sensor Head



iRobot Hand



75% new:

more agile, able to carry its own power source, run with a new adjustable hydraulic pump and move without a safety tether or communications cable.

3.7 kWh lithium-ion battery pack

Arms are lower to enhance push-up performance, but it makes Egress harder.

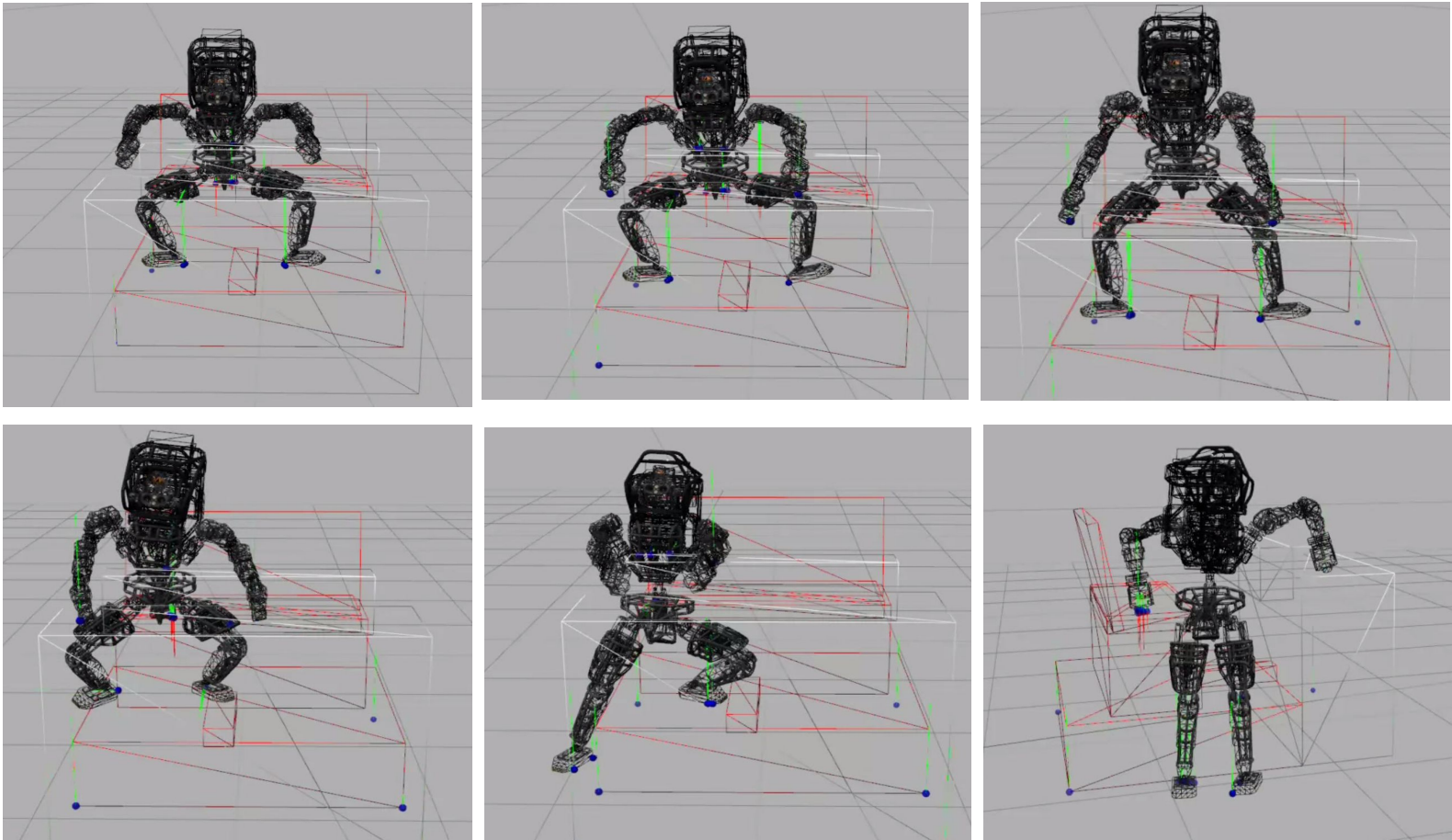
Challenges



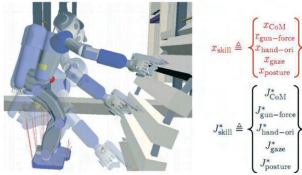
Contact-rich motion planning

Discrete decision: where to make contacts with hands, feet, and the hip

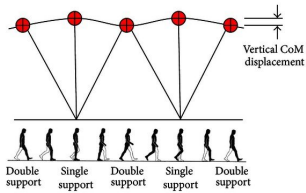
Continuous decision: how to move from one pose to another without falling



Related work

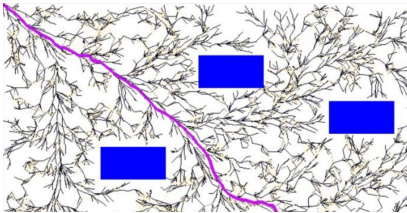


Inverse kinematics/dynamics based methods [Sentis2010a,Sentis2006]
 Solve QP problem
 Singularities

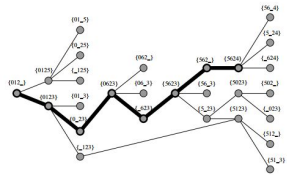


Plan using a simple model and then solve full-body motion [Feng2014]
 Hard to find feasible full-body trajectories in highly constrained space

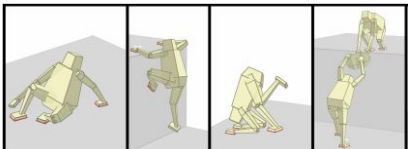
Gradient-based trajectory optimization (relies on GOOD initial trajectory)



Sampling-based trajectory searching [LaValle2001,Kuffner2000]
 RRT, RRT-connect, RRT* with rejection
 with projection (Monte Carlo)



Free climbing problem: search a contact graph to determine candidate stances and then solve continuous trajectory [Hauser2008a]



Contact invariant optimization (simulation results are promising)

Robot model

Floating base dynamics model:

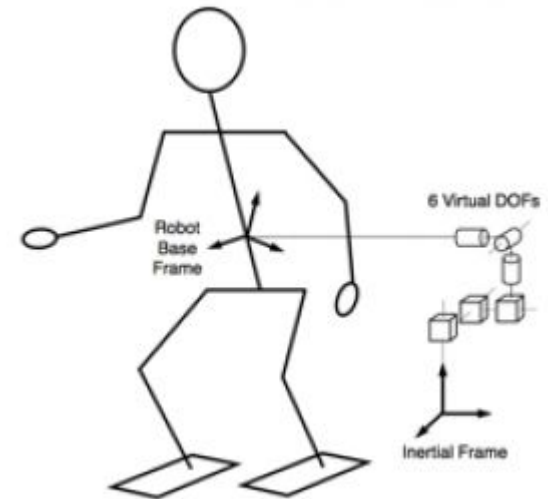
$$\boxed{M(q)\ddot{q}} + \boxed{N(q, \dot{q})\dot{q}} + \boxed{h(q)} = B\tau + \sum_{i=1}^n J_i^T f_i$$

inertial term centrifugal and coriolis term gravity term

where $q := [x_b, \theta_b, \theta]^T$

For static poses:

$$h(q) = B\tau + \sum_{i=1}^n J_i^T f_i$$



Static pose optimization

minimize
 q, τ, f_1, \dots, f_n

$$C_p(q, \tau, f_1, \dots, f_n)$$

subject to

$$C_\sigma(q) = 0 \quad \leftarrow \text{contact constraints}$$

$$h(q) = B\tau + \sum_{i=1}^n J_i^\top f_i \quad \leftarrow \text{equilibrium constraints} \quad (1)$$

$$f_{i_{min}} \leq f_i \leq f_{i_{max}} \quad \leftarrow \text{contact force constraints}$$

$$q_{min} \leq q \leq q_{max} \quad \leftarrow \text{range of motion constraints}$$

$$\tau_{min} \leq \tau \leq \tau_{max}, \quad \leftarrow \text{joint actuation constraints}$$

Contact-rich motion planning

$$\min_{\xi_1, \xi_2, \dots, \xi_M, \sigma_1, \dots, \sigma_N} \sum_{i=1}^M \int_0^1 c(\xi_i(t), \sigma_i, i) dt$$

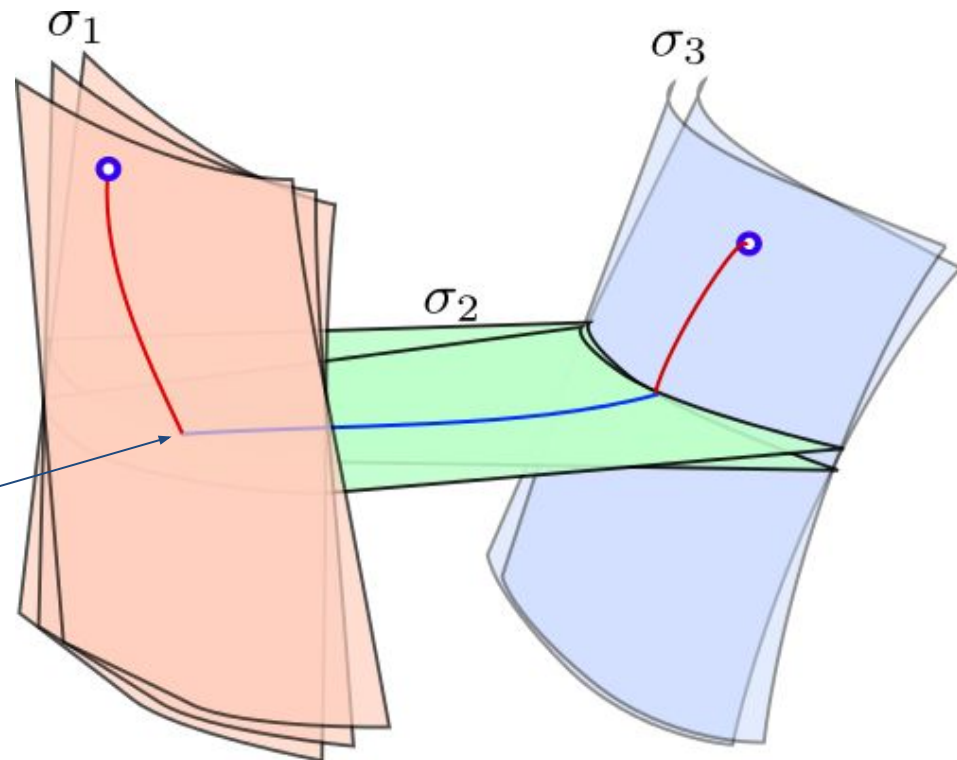
s.t.

$$C_{\sigma_i}(\xi_i(t)) = 0 \quad \forall t \in [0, 1] \quad i \in [1, M]$$

and other constraints

Connectivity:

$$\xi_i(1) = \xi_{i+1}(0) \quad \forall i \in [1, M-1]$$



Contact point/static pose sampling

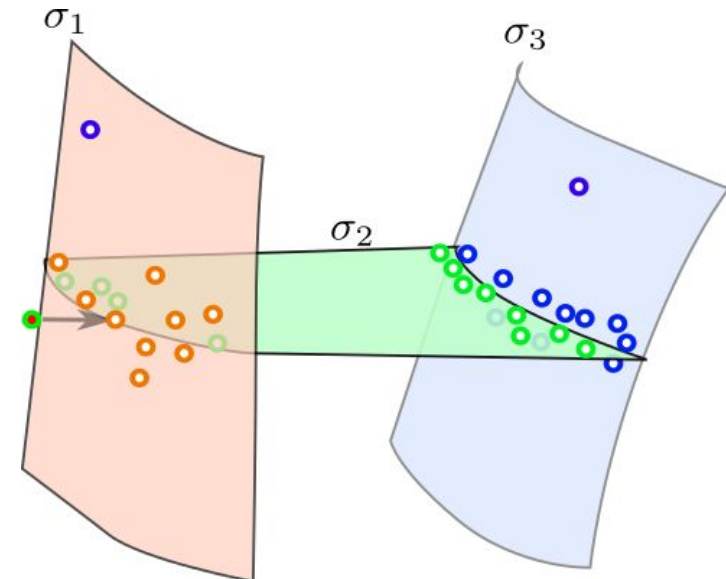
Human experience (mimic humans):

1. contact mode (number of contacts) and possible contact regions
2. seed poses

Random sampling (exploring):

1. Sample contact points in specified regions (Halton quasi-random)
2. Sample poses around seed poses

Satisfy all constraints by optimization (project the sampling points to constraint manifolds)

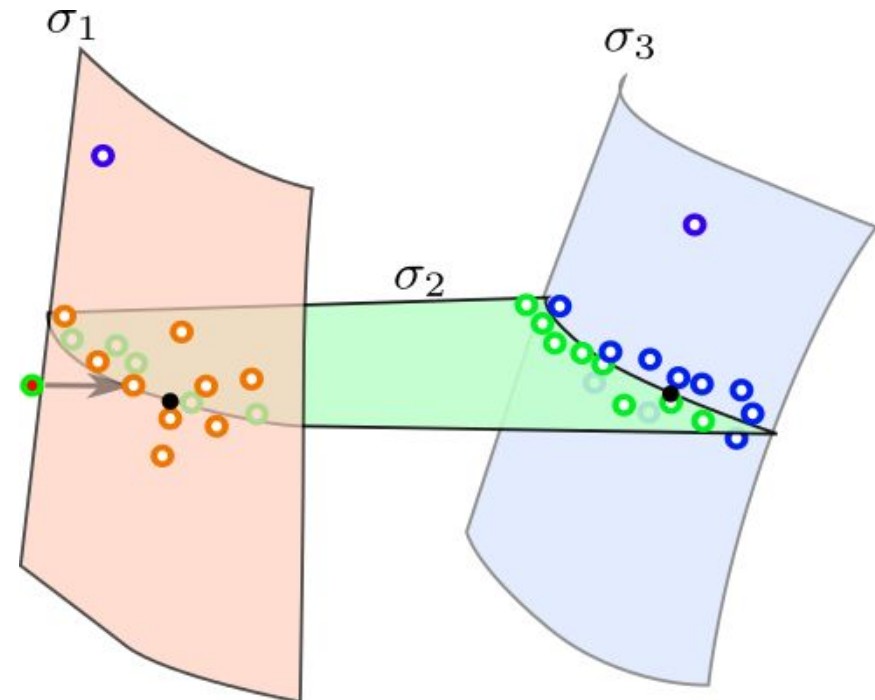
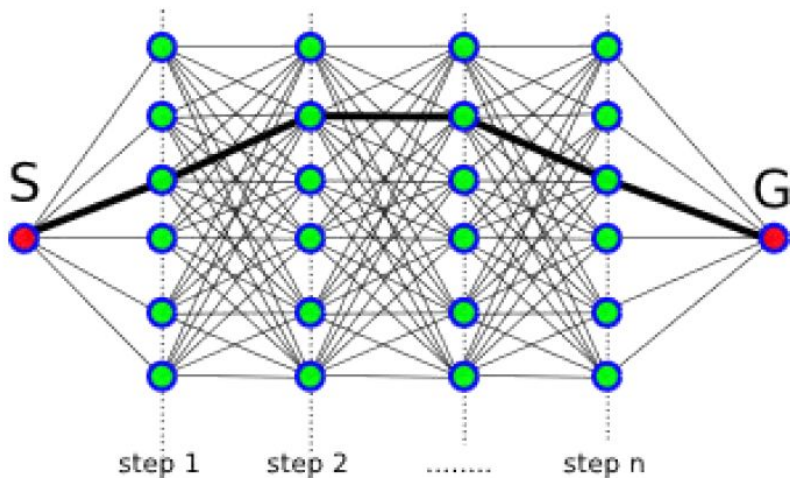


Waypoint optimization

$$\min \sum_{i=1}^{M-1} [C_p(\xi_i(1), i) + C_c(\xi_i(1), \xi_{i+1}(0))]$$

Connectivity penalty:

$$C_c(q, q') = w_1 \left(\sum_i \|p_i(q) - p_i(q')\|^2 \right) + w_2 \|B(q - q')\|^2$$





(a) Phase 0



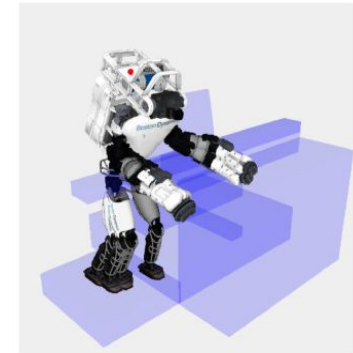
(b) Phase 1



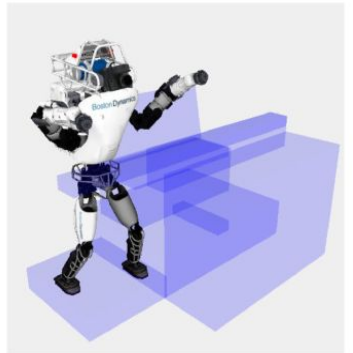
(c) Phase 2



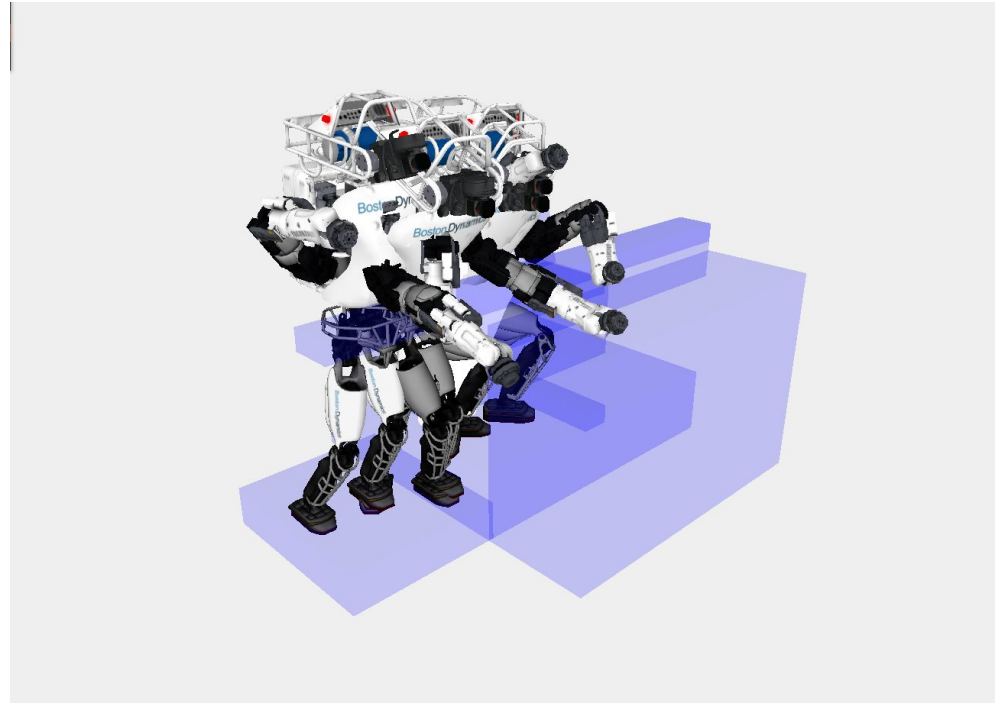
(d) Phase 3



(e) Phase 4



(f) Phase 5



Waypoint optimization result

Contact and pose sampling result

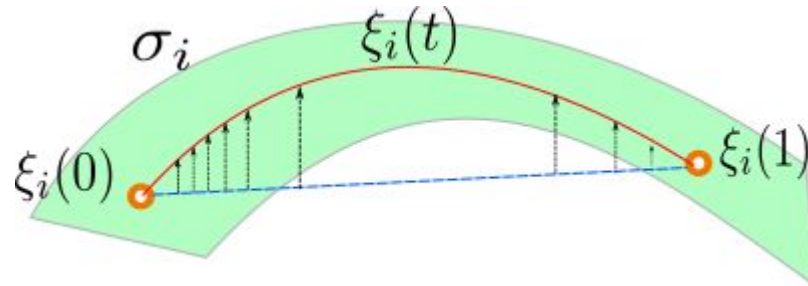
Online pose optimization

Having the waypoints, we do interpolation to generate a rough plan.

Option 1: Optimize a feasible trajectory based on the models and then track the trajectory (planning, won't work because of model error and uncertainties)

Option 2: Optimize a feasible pose based on models and measurements and then track the pose. (control, very robust)

$$\begin{aligned} \underset{\dot{q}}{\text{minimize}} \quad & \sum_i w_i \|J_i(q)\dot{q} - k_p^c(x_{d_i} - x_i) - k_d^c(\dot{x}_{d_i} - \dot{x}_i)\|^2 \\ & + w_d \|B\dot{q}\|^2 \\ \text{subject to} \quad & q_{min} \leq \dot{q}\Delta T + q \leq q_{max} \end{aligned} \tag{6}$$



Online pose control

Joint torque control: PD-forward controller

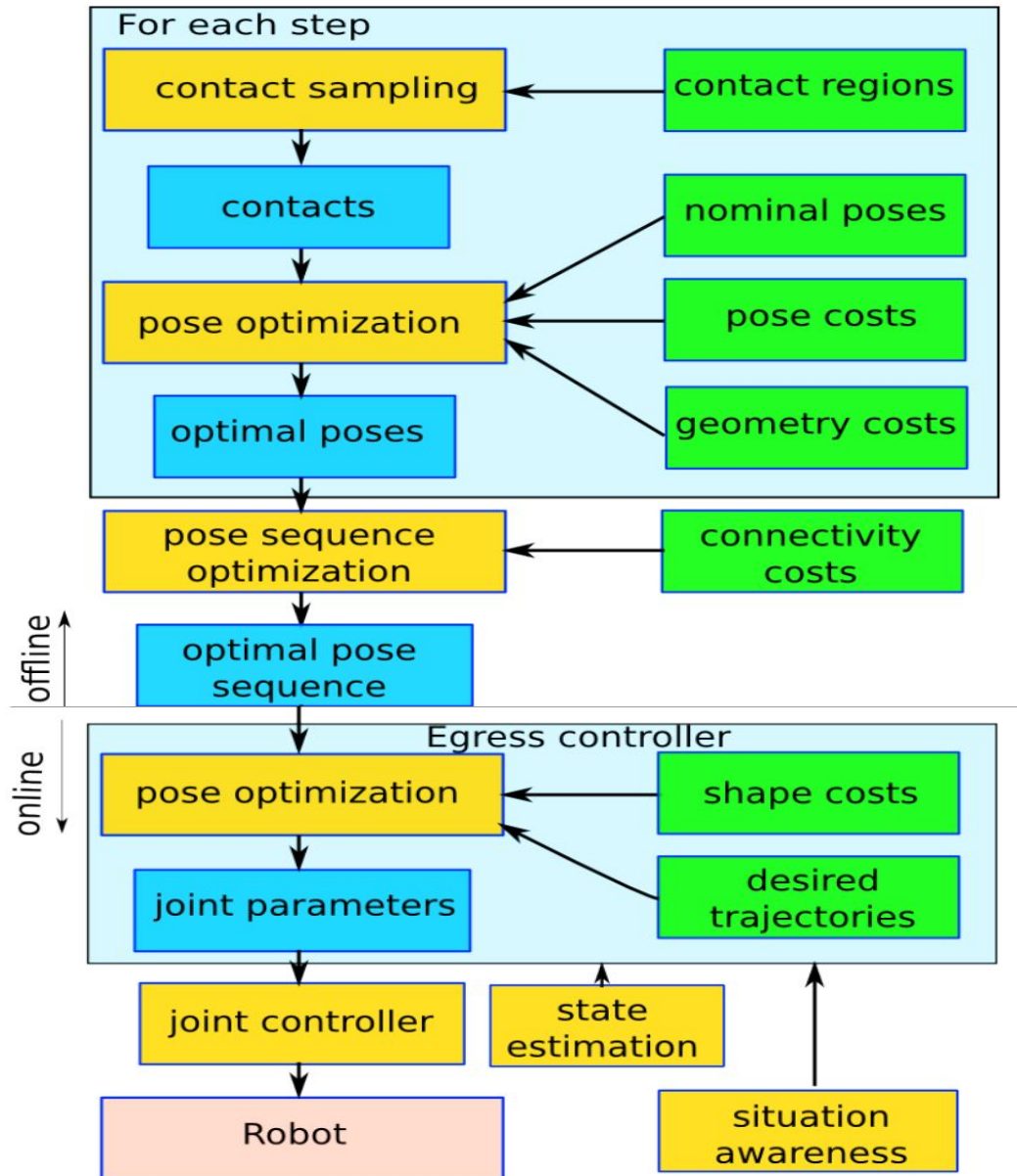
$$cmd = K_p(\theta_d - \theta) + K_d(\dot{\theta}_d - \dot{\theta}) + K_f(\tau_d - \tau), \quad (8)$$

Compliant control for foot touchdown

Floating-base state estimation (EKF):

- Auto-detect the stationary contact points as reference points
- Periodically match the contact predictions with their measurements

Software flowchart



Main UI

Forearm Status

joint	cal	en	Temp	I
L_UWY	1	1	69	10.0
L_MWX	1	1	79	9.0
L_LWY	1	1	89	8.0
R_UWY	1	1	99	7.0
R_MWX	0	1	109	6.0
R_LWY	1	1	119	5.0

Calibrate
Disable
Enable

Pressure

Nitrogen **77.7** PSI
Pump Inlet 0.0 PSI
Pump Supply 0.0 PSI

Temperature

Motor 0.0 °C
Motor Driver 0.0 °C
Pump Supply 0.0 °C


Pump Time 0.000 Hrs
Pump Speed 0 RPM

Voltage 200.0 V
Current 3.0 A
Time Left 90 Min
Amp Hours Left 20.0 Ah

BDI Mode: STAND
Custom Mode: TRAPEZOIDAL_VELT
Gains: Default Gain

START 1500
STOP

Closest to camera: 1.3041



/ocu/multisense/left/image_rect_color

Diameter 0.04 Activate neck_ry Down -0.17 Up Send
Length 0.05 Left Right Cylinder Discard

Step Motion Drill Motion Door Motion Debris Motion Plug Motion Egress Motion Valve Motion 2 Surprise Motion Steering Slider

StartStep Clear Steps List of Steps Undo

PLAN FAIL

Plan B
OffPlatform
Arm-Walk
Arm-Stair
AutoZHeight
ZeroZHeight

Nom. Walk
Set Foot Support
Shrimp! Straight

Planner Type FlatGroundLinearInterp
Step/Walk Type CMU_STEP

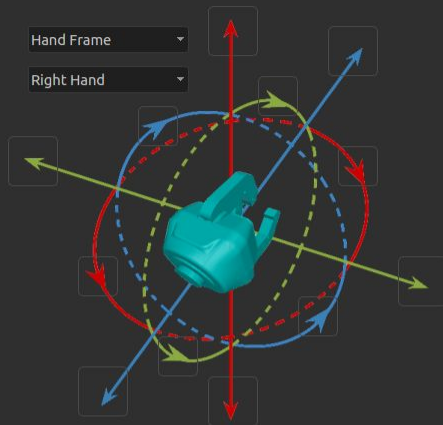
StanceWidth 0.46
Step Size 0.32
Step Width 0.20
Swing Height 0.05
Step Duration 2.50
Rotation 0.00
Steps Forward 0
Steps Left 0

step #	left/right	x	y	z	nx	ny	yaw	lift hgt	swing hgt
-1	L	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05

Add/Modify Delete Insert

Nudge

Hand Frame
Right Hand



Left Hand Right Hand

A B C A B C

Open Close Open Close

Persistent Persistent

Hand Power On Off

ACCEPT TRAJ
REJECT TRAJ

Manipulation
Control
Joint Sliders

Egress Task UI

The image shows a software interface for an Egress Task. At the top, there is a navigation bar with tabs for different motion types: Step Motion, Drill Motion, Door Motion, Debris Motion, Plug Motion, Egress Motion (selected), Valve Motion 2, Surprise Motion, and Steering Slider. Below the navigation bar, the interface is divided into several sections:

- Control Buttons:** A row of buttons including "Disable", "Enable/Reset", "Reset Yaw", "Stand Inside", "Pelvis", "Left Foot Swing", and "Move Inside".
- Navigation Buttons:** A row of buttons including "Load Poses", "Goto Previous", "Goto Current", and "Goto Next".
- Command List:** A scrollable text area containing the following commands:

```
RESET_ROOT1  
RESET_YAW1  
SIT  
RIGHT_FOOT_OUT  
RIGHT_FOOT_DOWN1  
STAND UP INSIDE
```
- Navigation Buttons (Bottom):** A row of buttons including "NEXT" and "Ack".
- Control Buttons (Right Side):** A grid of buttons for specific actions: "Left Foot Down", "Right Foot Down", "Dual Arm Pos", "Arm Ctrl", "Left Wrist", "X+", "Right Wrist", "Y+", "Z+", "Z-", "Y-", "Left foot", "X-", and "Right Foot".
- Emergency Stop:** A prominent red button labeled "Stop".
- Status Area:** A scrollable area at the bottom left, currently empty, with the label "Egress Status" to its right.



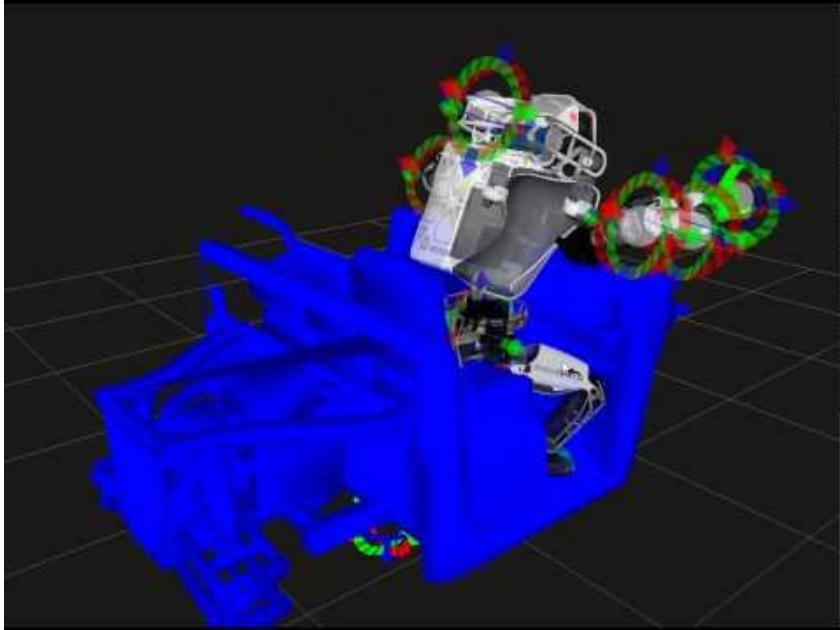


Thanks!

For more details:

C. Liu, C. G. Atkeson, S. Feng and X. Xinjilefu, "Full-body motion planning and control for the car egress task of the DARPA robotics challenge," *2015 IEEE-RAS 15th International Conference on Humanoid Robots (Humanoids)*, Seoul, 2015, pp. 527-532.





Our approach - big picture

1. Random sampling of contacts and poses
2. Offline trajectory waypoints optimization, especially for where there are contact changes
3. Online pose optimization to handle model error and maintain contacts and balance
4. Force feedback control plus tele-assist to handle uncertainties



Common challenges

- Keep balance
- Many DoFs ($29=12 + 8 + 3 + 6$)
- Highly nonlinear
- Contact constraints
- Weak waist and arms
- Limited range of motion

Special challenges for Egress

- Highly constrained space
- Many contacts
- Undetectable collision
- Car suspension and seat cushion

