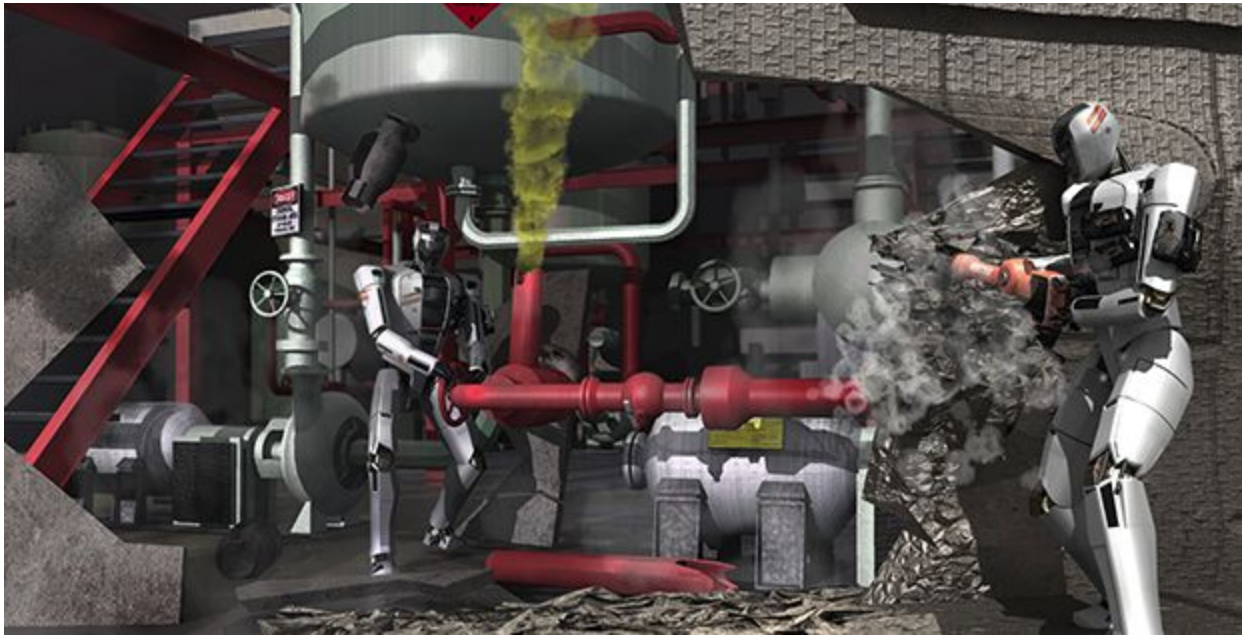
Full-body motion planning and control for the egress task of the DARPA Robotics Challenge

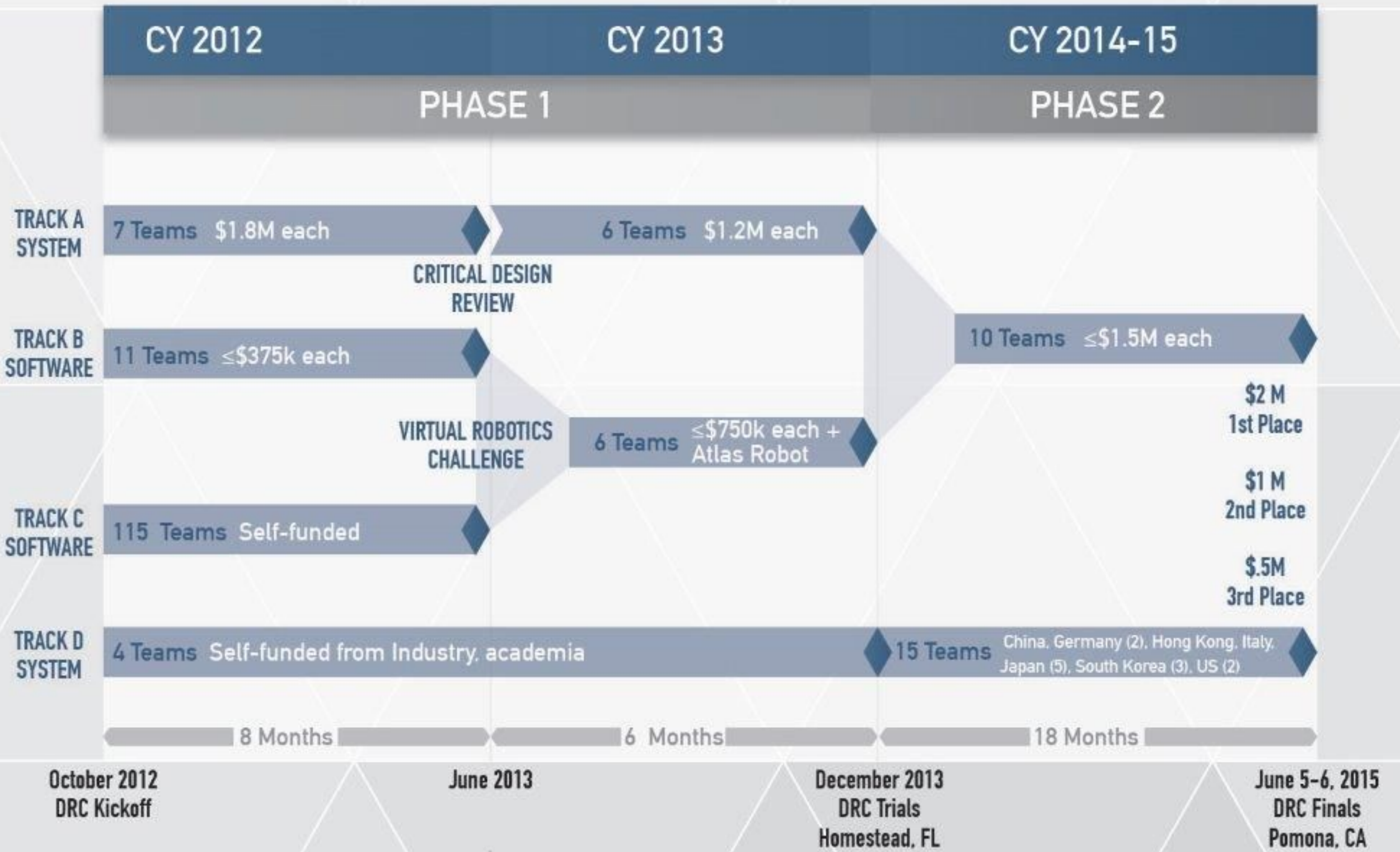
Outline

- 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

DARPA ROBOTICS CHALLENGE FINALS 2015

DRC Finals 25

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.

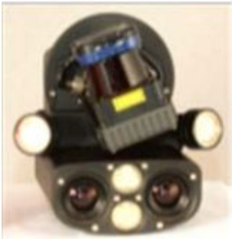
- the center of mass of the robot (with on accessories) must do task 1 and start task 2 inside the unmodified vehicle. A practical test is the robot may passively stay in the unmodified vehicle when all hands and grips and attachments are release

- 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.

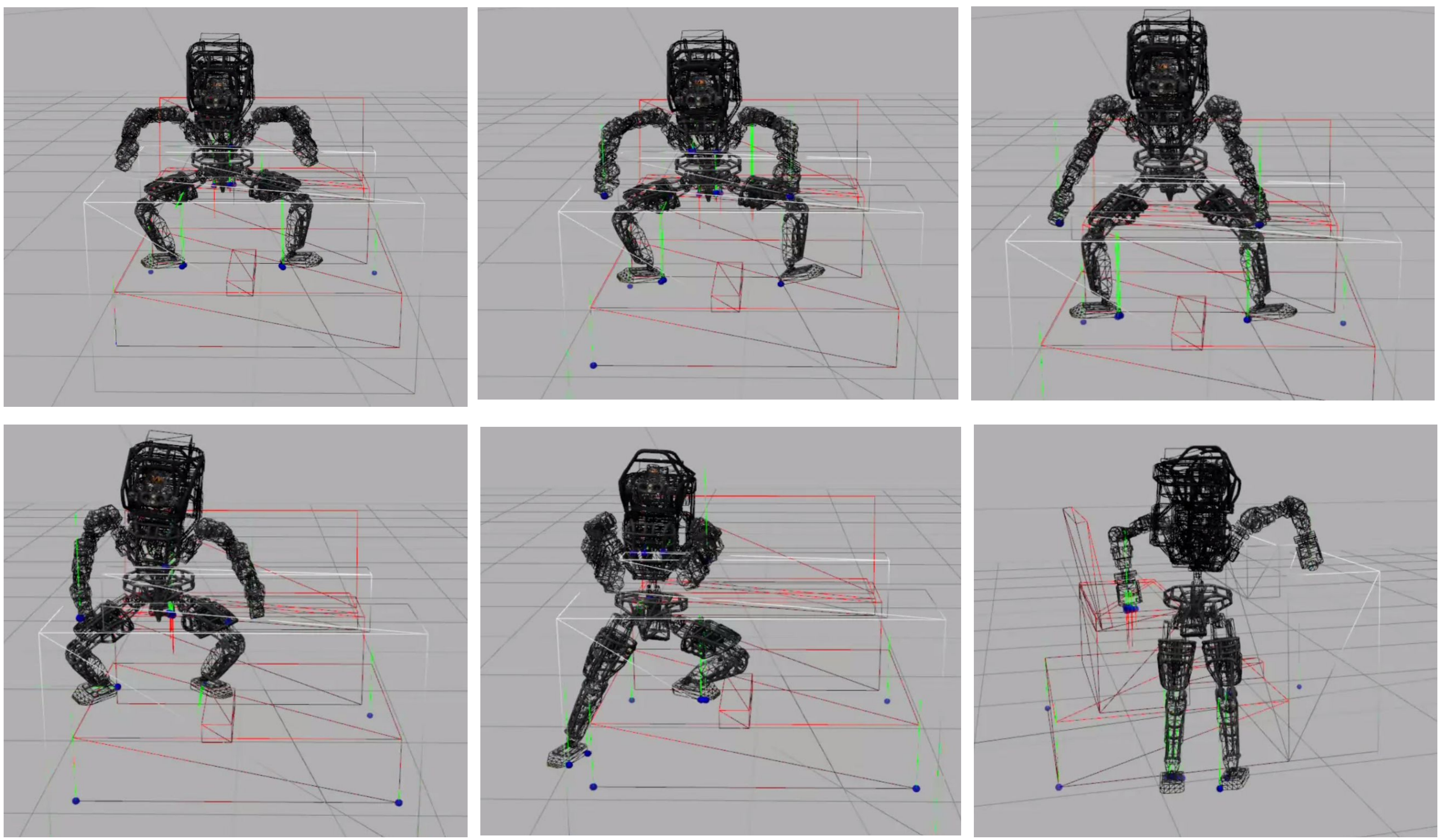
3.7 kWh lithium-ion battery pack

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

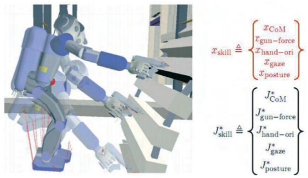
Challenges

Contact-rich motion planning

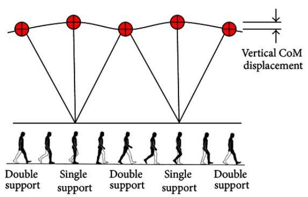
Discrete decision: where to make contacts with hands, feet, and the hip
Continuous decision: how to move from one pose to another without falling



Related work



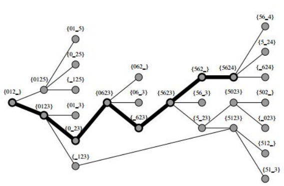
Inverse kinematics/dynamics based methods [Sentis2010a,Sentis2006]
- Solve QP problem
- Singularities



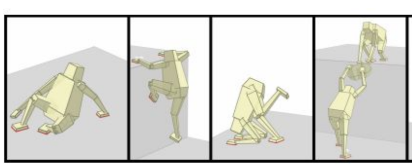
Plan using a simple model and then solve full-body motion [Feng2014]
- Hard to find feasible full-body trajectories in highly constrained space

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:

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

inertial term

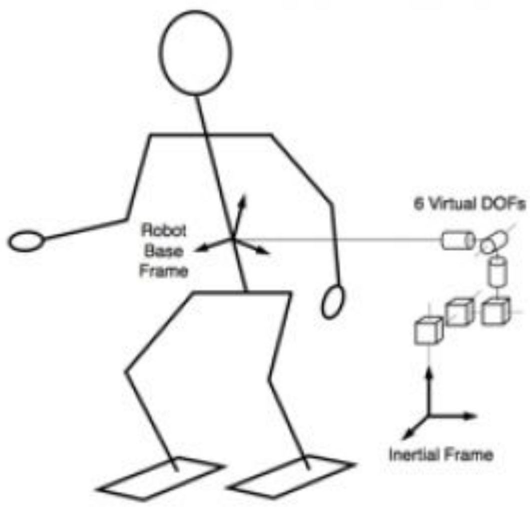
centrifugal and coriolis term

gravity term

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

For static poses:

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



Static pose optimization

$$\underset{q,\tau,f_1,\ldots,f_n}{\text{minimize}} \quad C_p(q, \tau, f_1, \ldots, f_n)$$

$$\text{subject to} \quad C_\sigma(q) = 0$$

contact constraints

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

equilibrium constraints

$$f_{i_{min}} \leq f_i \leq f_{i_{max}}$$

contact force constraints

$$q_{min} \leq q \leq q_{max}$$

range of motion constraints

$$\tau_{min} \leq \tau \leq \tau_{max},$$

joint actuation constraints

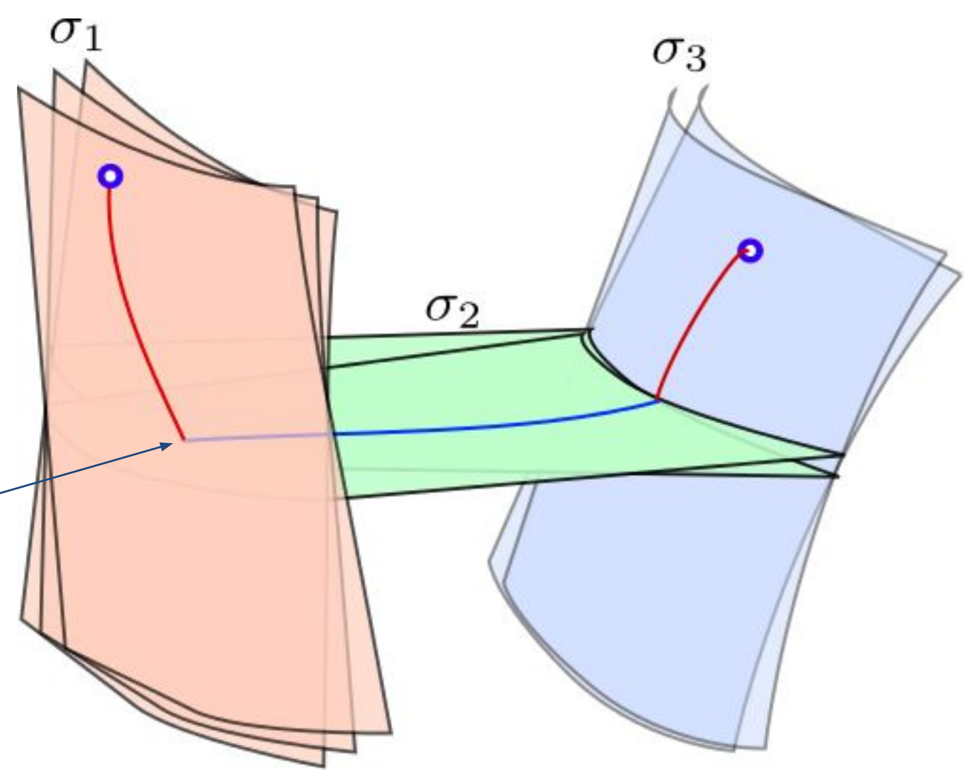
Contact-rich motion planning

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

s.t.

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

and other constraints



Connectivity:

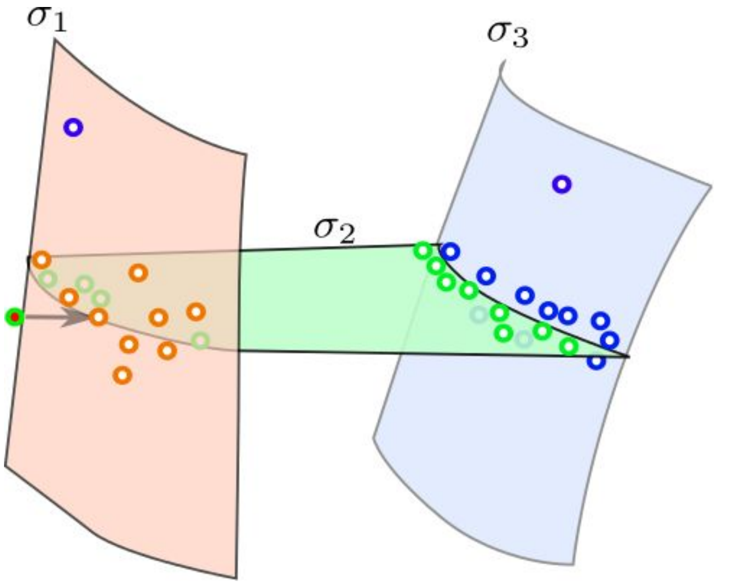
$$\xi_i(1) = \xi_{i+1}(0) \; \forall i \in [1, M-1]$$

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)

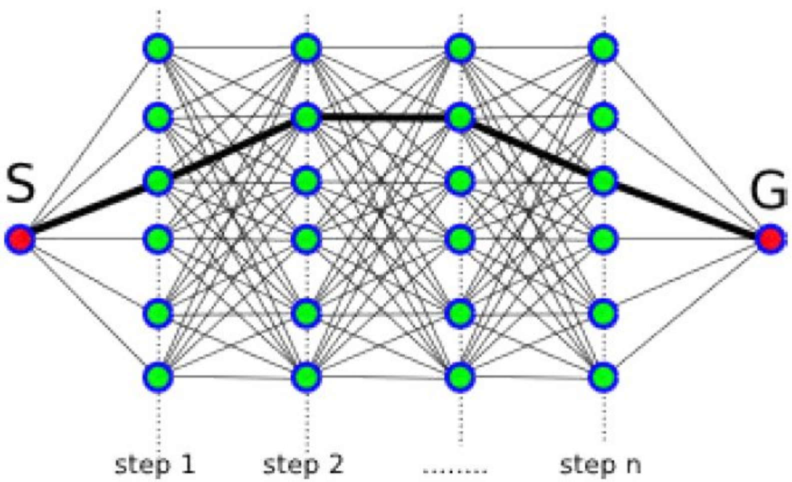


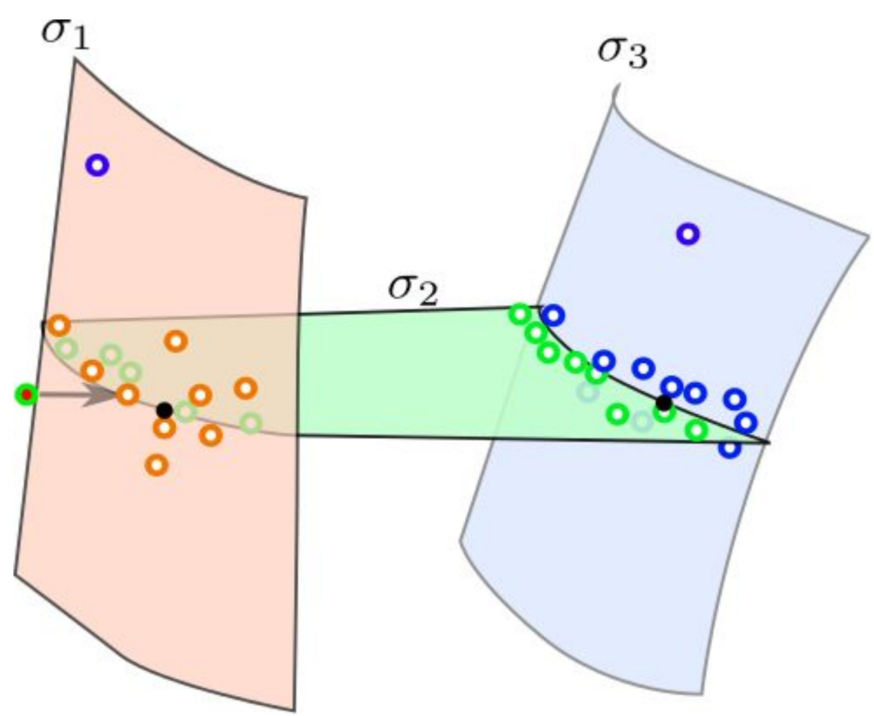
Waypoint optimization

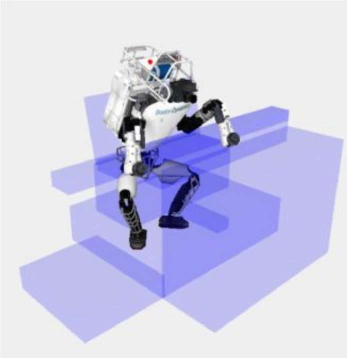
$$\min \sum_{i=1}^{M-1} \left[C_p(\xi_i(1), i) + C_c(\xi_i(1), \xi_{i+1}(0)) \right]$$

Connectivity penalty:

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







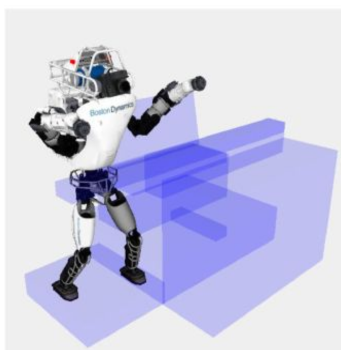
(a) Phase 0

(b) Phase 1

(c) Phase 2

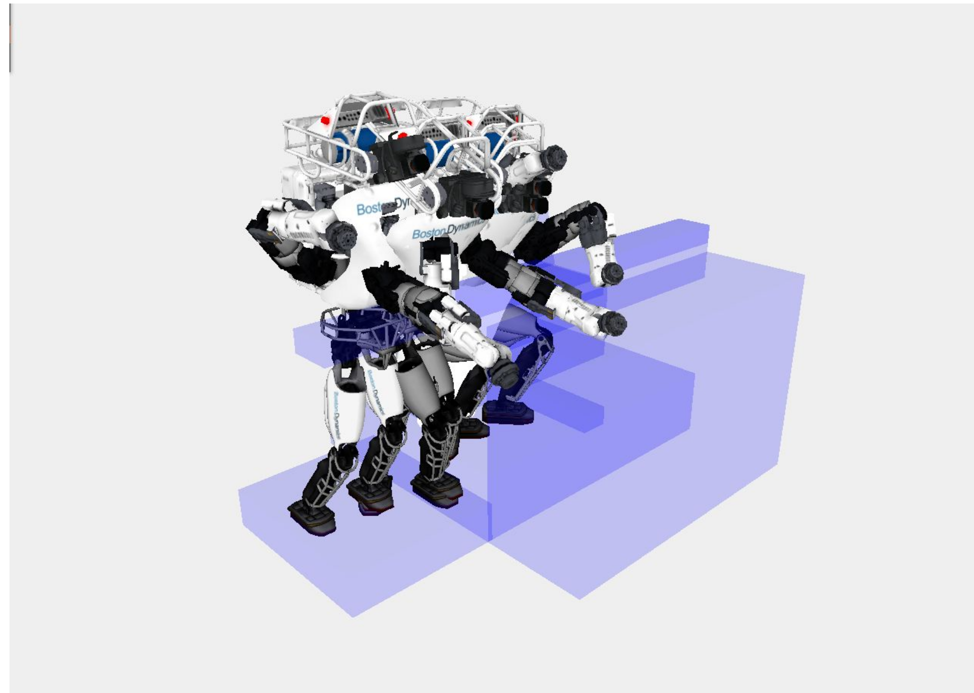
(d) Phase 3

(e) Phase 4



(f) Phase 5

Contact and pose sampling result



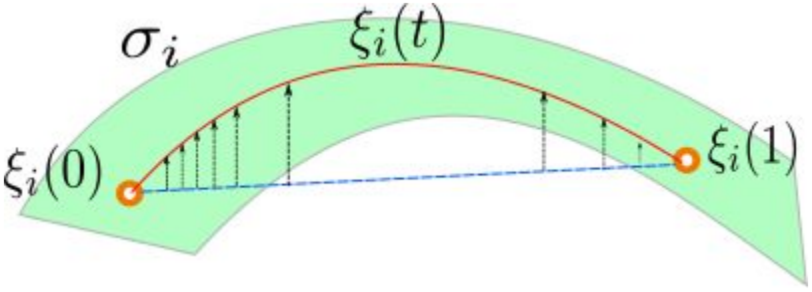
Waypoint optimization result

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

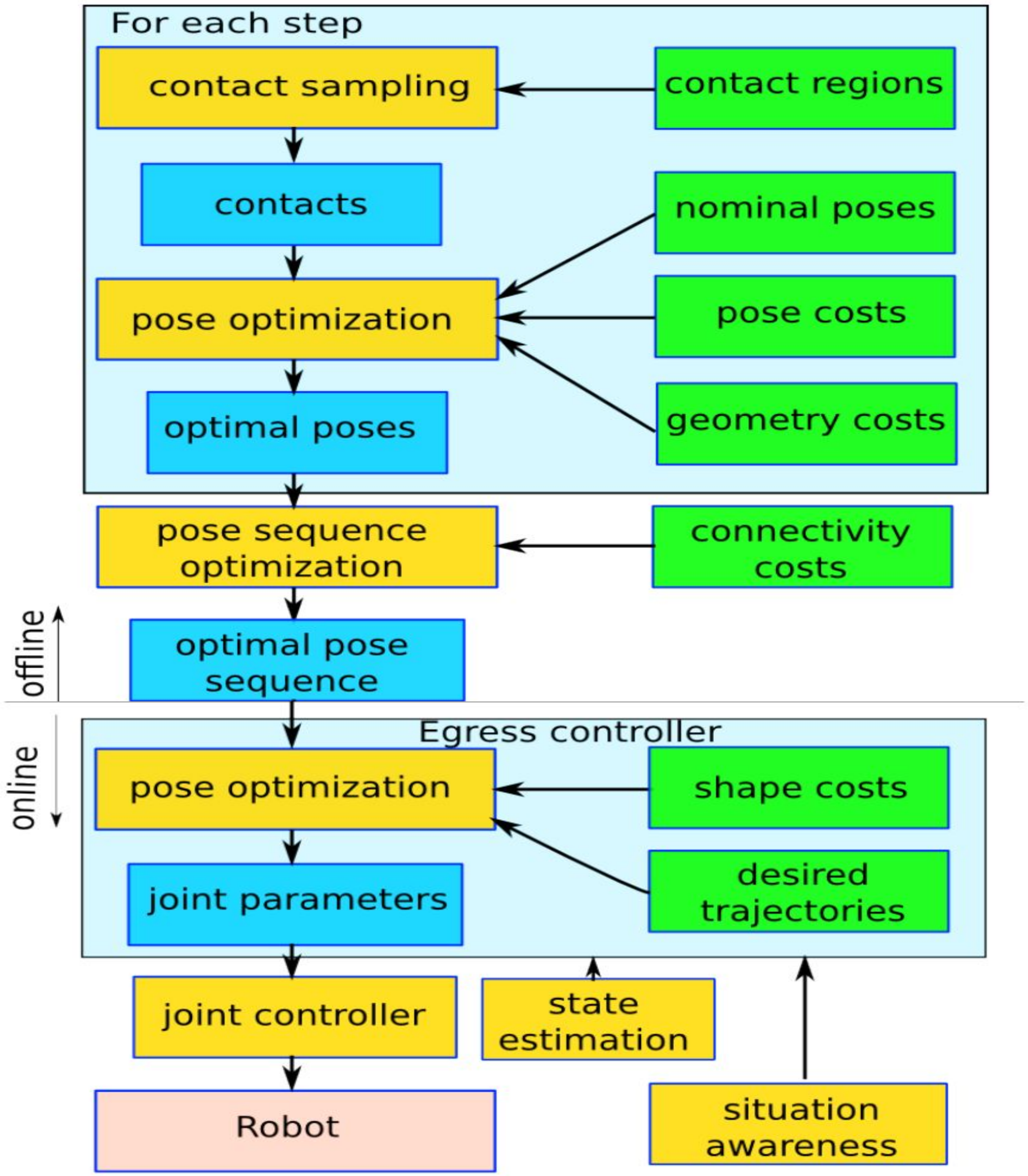
$$cmd = K_p(\theta_d - \theta) + K_d(\dot{\theta}_d - \dot{\theta}) + K_f(\tau_d - \tau), \qquad (8)$$

Compliant control for foot touchdown

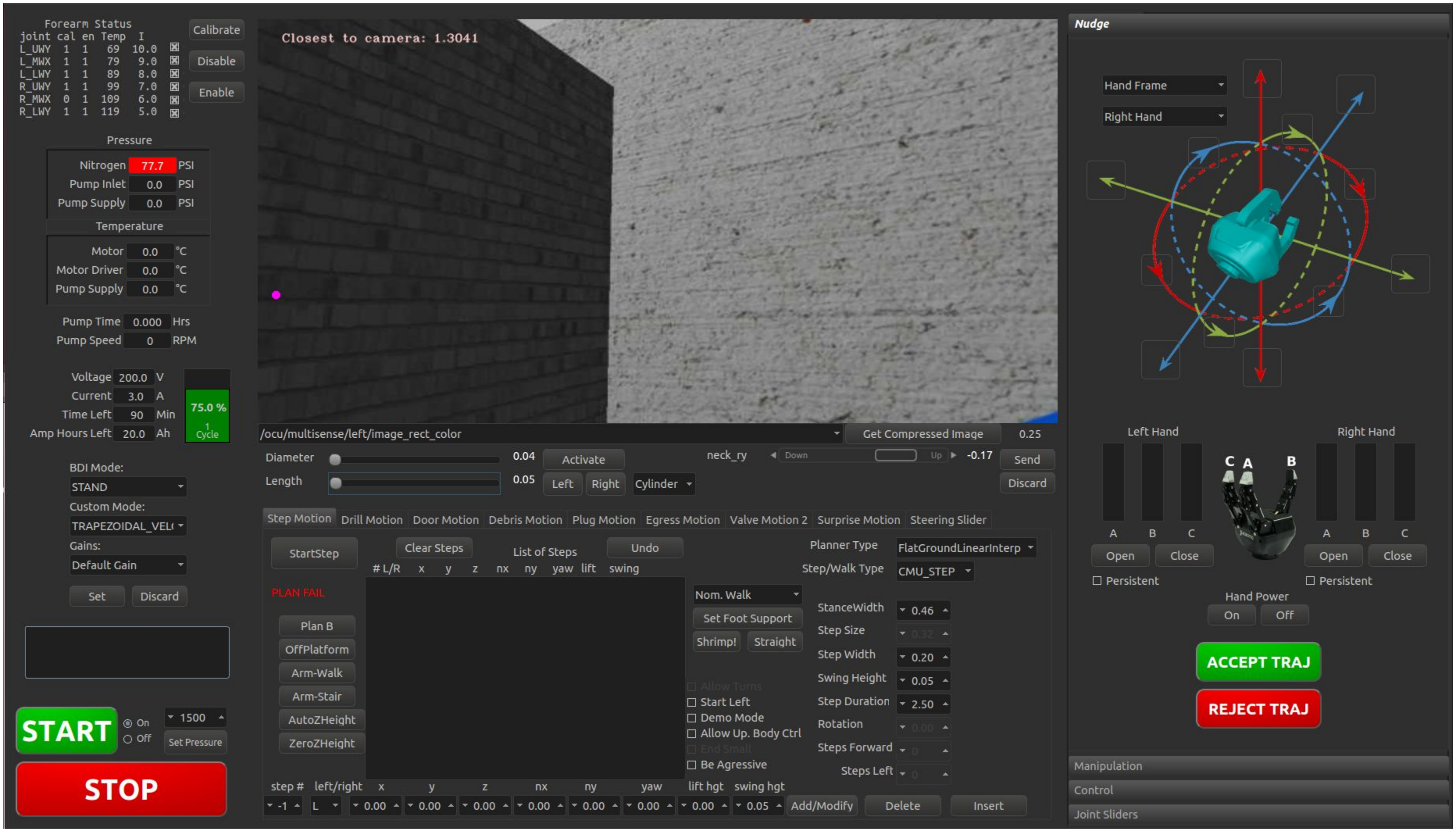
Floating-base state estimation (EKF):

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

Software flowchart

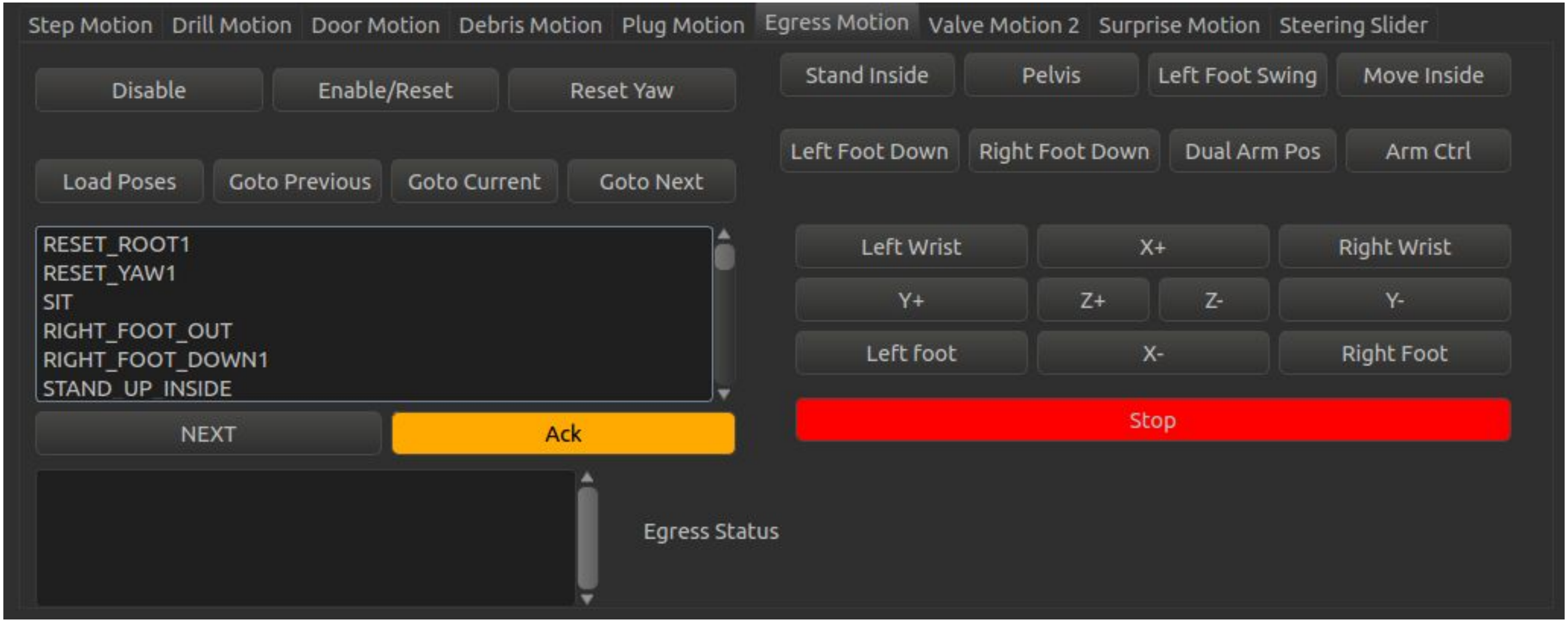


Main UI



Forearm Status
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
75.0 %
BDI Mode:
STAND
Custom Mode:
Gains:
Default Gain
Set
Discard
START
STOP
Set Pressure
Closest to camera: 1.3041
/ocu/multisense/left/image_rect_color
Get Compressed Image
Diameter
Length
Activate
Left
Right
Cylinder
neck_ry
Send
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
Planner Type
FlatGroundLinearInterp
Step/Walk Type
CMU_STEP
Nom. Walk
Set Foot Support
Shrimp!
Straight
StanceWidth
Step Size
Step Width
Swing Height
Step Duration
Rotation
Steps Forward
Steps Left
Start Left
Demo Mode
Allow Up. Body Ctrl
Be Agressive
Add/Modify
Delete
Insert
Nudge
Hand Frame
Right Hand
Left Hand
Right Hand
Open
Close
Persistent
Hand Power
On
Off
ACCEPT TRAJ
REJECT TRAJ
Manipulation
Control
Joint Sliders

Egress Task UI



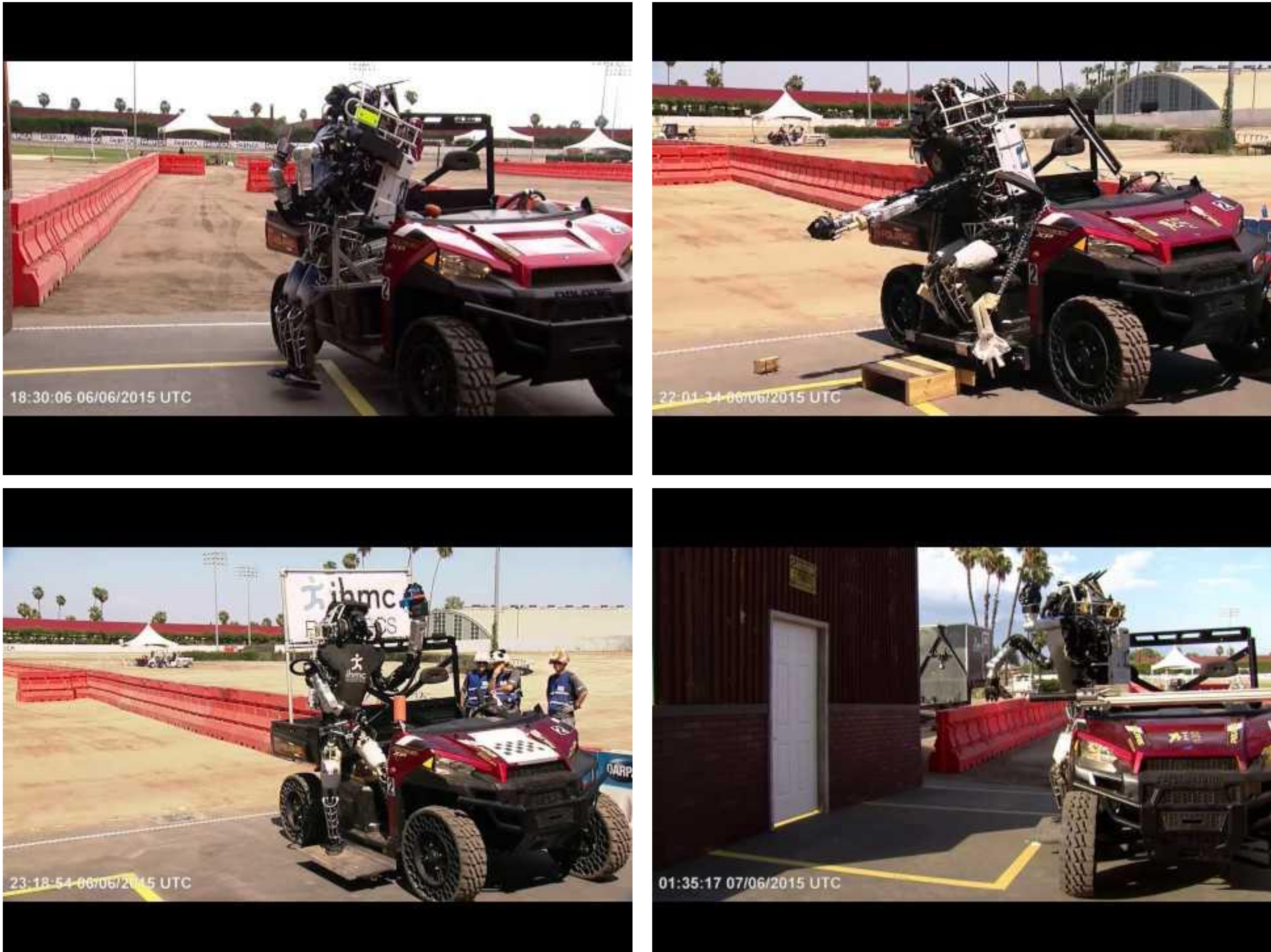

WPI


HECTOR

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.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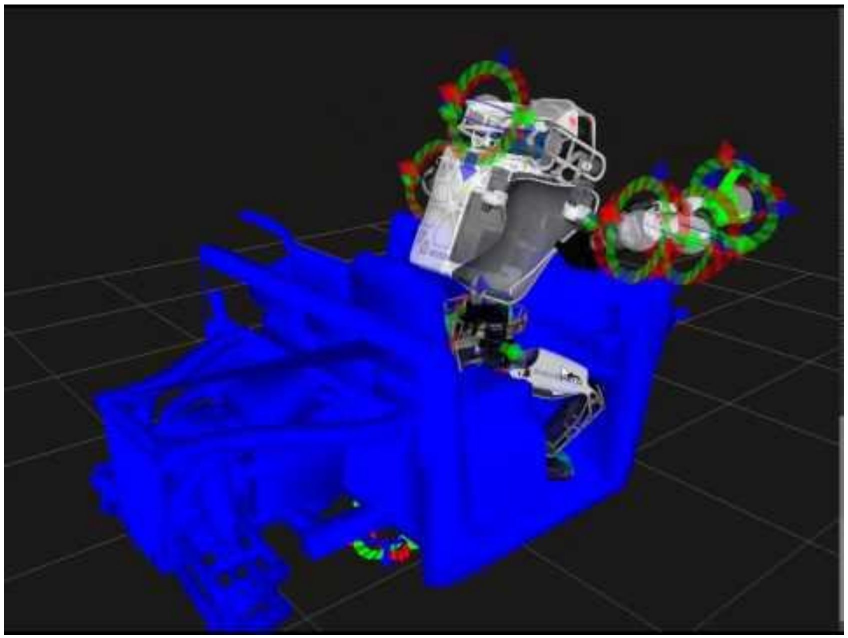
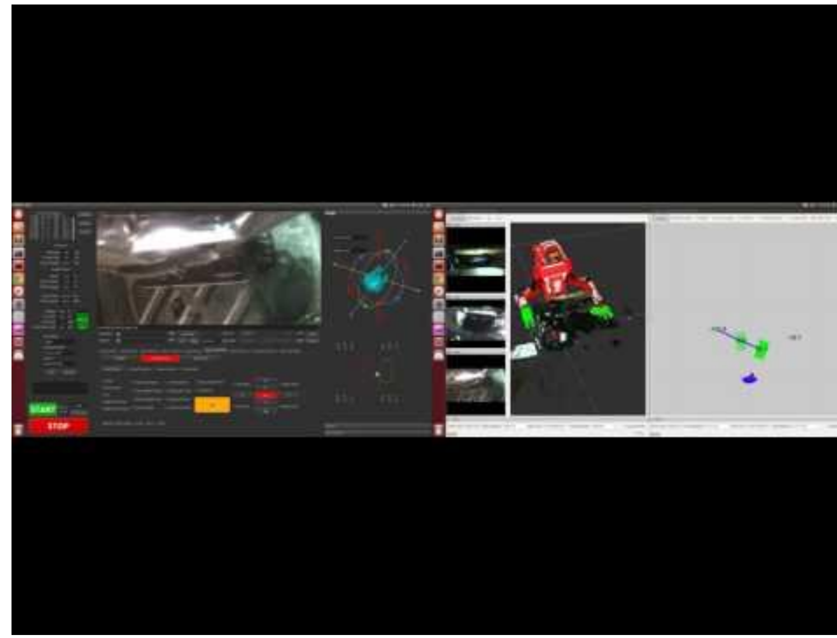



START
STOP

Our approach - big picture

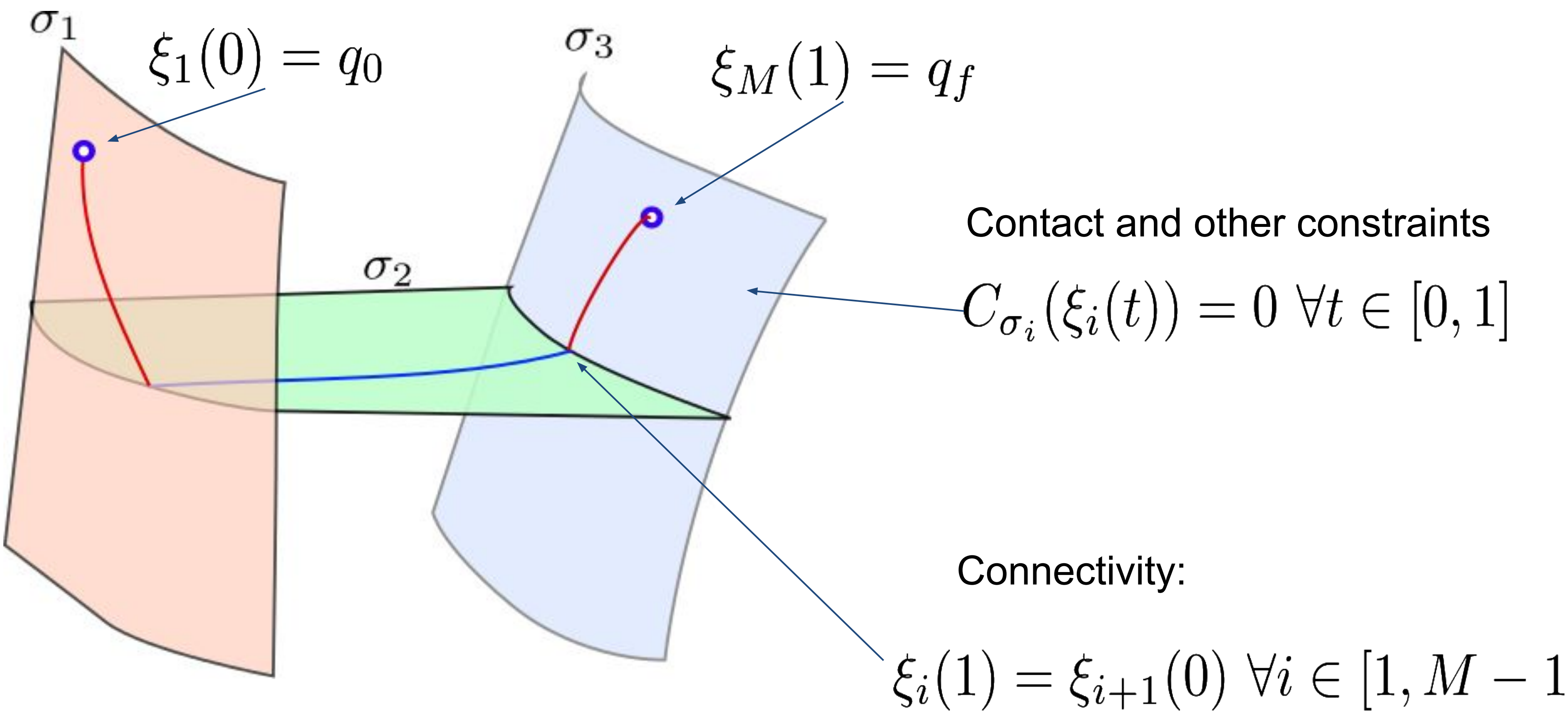
1. Random sampling of contacts and poses
2. Offline trajectory waypoints optimization, especially for where there are contact changes
3. Online pose optimization to handle model error and maintain contacts and balance
4. Force feedback control plus tele-assist to handle uncertainties

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



σ_1
$\xi_1(0) = q_0$
σ_3
$\xi_M(1) = q_f$
σ_2
Contact and other constraints
$C_{\sigma_i}(\xi_i(t)) = 0 \ \forall t \in [0, 1]$
Connectivity:
$\xi_i(1) = \xi_{i+1}(0) \ \forall i \in [1, M-1]$