Motion Planning of Ladder Climbing for Humanoid Robots

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Challenges

“Human strategies can and do fail when applied directly to humanoids.”

Although seemingly straightforward for humans, this task is quite challenging for humanoid robots for the following reasons:

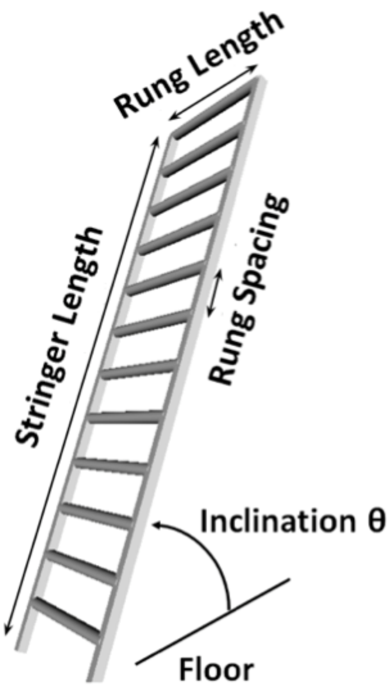
- **Differences from human kinematics (number of joints, limb lengths, joint ranges, and etc.)**
- **Significant contact forces**
- **Simultaneous coordination of 3 or 4 limbs in contact**
- **Limited motor torque and shock tolerance**

Contributions / Outline

- **General planning approach**
  Accepts arbitrary robot models, ladder models,
  and surrounding obstacles.
- **Primitive-based method (7 primitives)**
  Adapts knowledge from previous plans
  or from human experts to help converge to reasonable solutions
- **Planner / Simulation cycle**
  Plan with simplified planner model, design, test, and verify.
  Candidate hardware changes were factored into this cycle.
- **Identified variables in ladder-climbing capabilities**
  Grip strength, hip flexibility, and Lower-leg thickness, foot friction, and
  high-force static poses.

Ladder Specification as Input

Major Ladder properties are **ladder inclination**, **rung spacing**, **stringer width**, and **cross- sectional geometries**.



3m	Length of stringers
0.6m	Width between stringers
75°	Slope of ladder (angle of elevation from ground)
0.25m	Distance between center of two rungs along the stringer
1	Stringer shape parameter (1: cuboid, 0: cylindrical)
0.05m	Width of stringers *
0.05m	Thickness of stringers *
0.025m	Radius of stringers †
0	Rung shape parameter (1: cuboid, 0: cylindrical)
0.05m	Height of rungs *
0.10m	Thickness of the rungs *
0.03m	Radius of rungs †

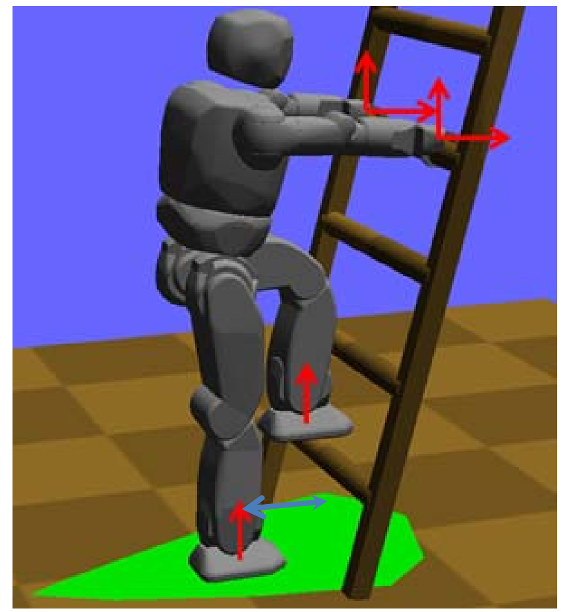
* **required for cuboidal shape**
† **required for cylindrical shape**

Ladder Climbing Planner

- Hubo's ladder climbing motion
  - Mount on the ladder
  - Climb to higher rung (5x-8x)
  - Dismount (Future work…)
- Input variables
  - Ladder specification: slope, rung spacing, etc.
  - Initial rung holding
- Output: a kinematically feasible path

Contact Modeling

- A *hold*, or contact of a single robot link with environment
  - Modeled as point-contacts:
    - Two per hand, one per foot
  - Encodes constraints for one limb.
- A *stance (δ)* can be 3 or 4 holds
- Coulomb friction coefficient:
  - u = 0.40
- Test stability using Bretl's method
  - More inclusive criteria than ZMP
  - Expanded support polygon (green) is projected stable region of COM



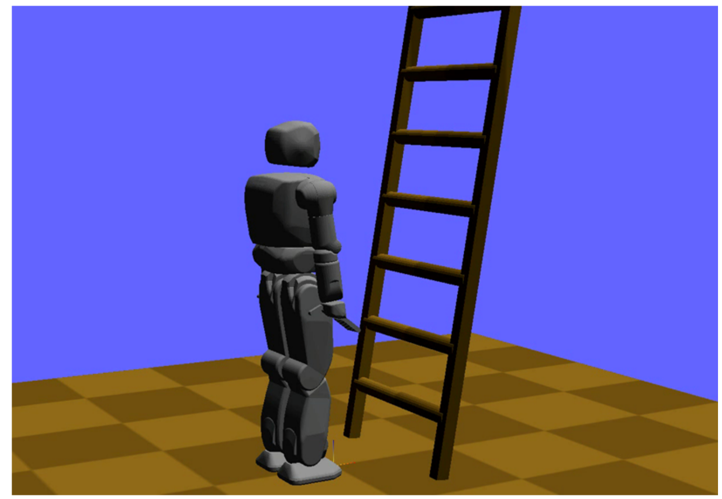
Point-contacts and corresponding support polygon

[17] T. Bretl, "Motion Planning of Multi-Limbed Robots Subject to Equi-librium Constraints: The Free-Climbing Robot Problem," International Journal of Robotics Research, no. 4, pp. 317–342, Apr. 2006.

Motion Primitives for Climbing Motion

- Motion Primitive (MP)
  - Releases and places one limb at a new contact
  - Rest holds (h_d) unchanged
- Climbing motion (7 primitives)
  - Mounting ladder primitives

placeHands → placeLFoot → placeRFoot

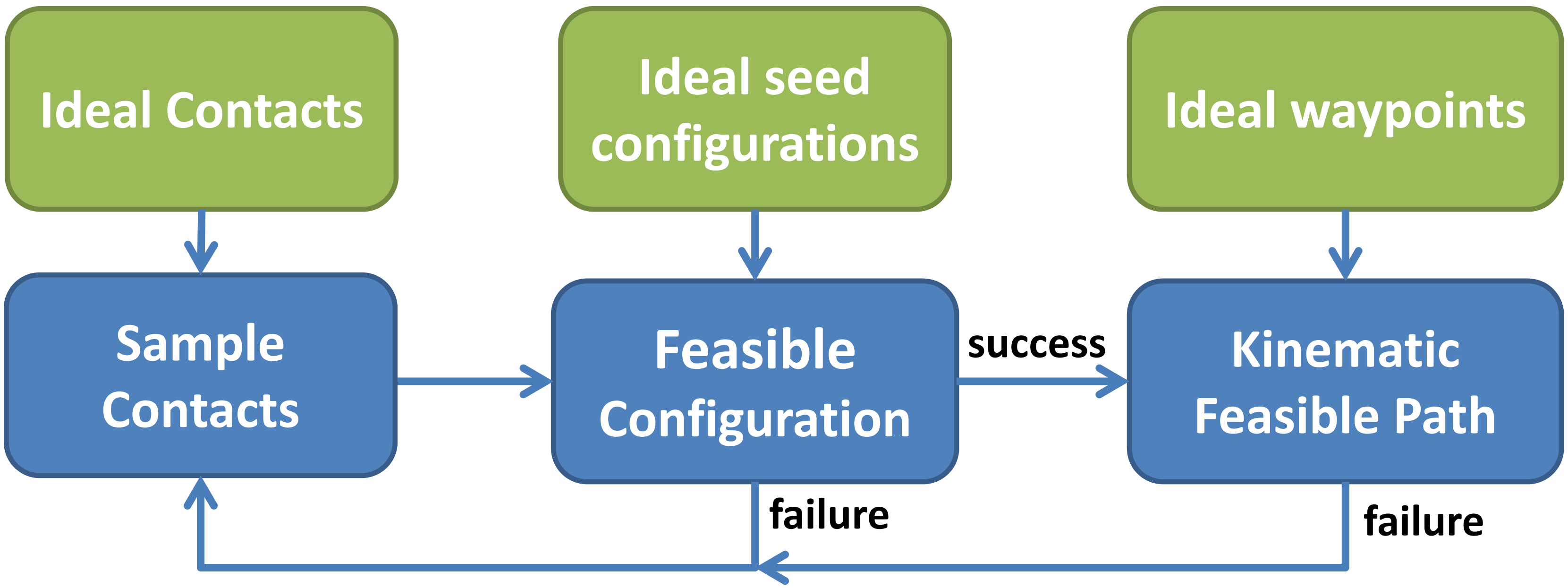


  - Climbing primitives

moveLHand → moveRHand → moveLFoot → moveRFoot

Planning with Ideal Motion

- Design ideal MPs with experiences from human experts.
- Adapt ideal MPs to new problems.
- Perturb around an "ideal" motion to achieve an ideal contact via an ideal path



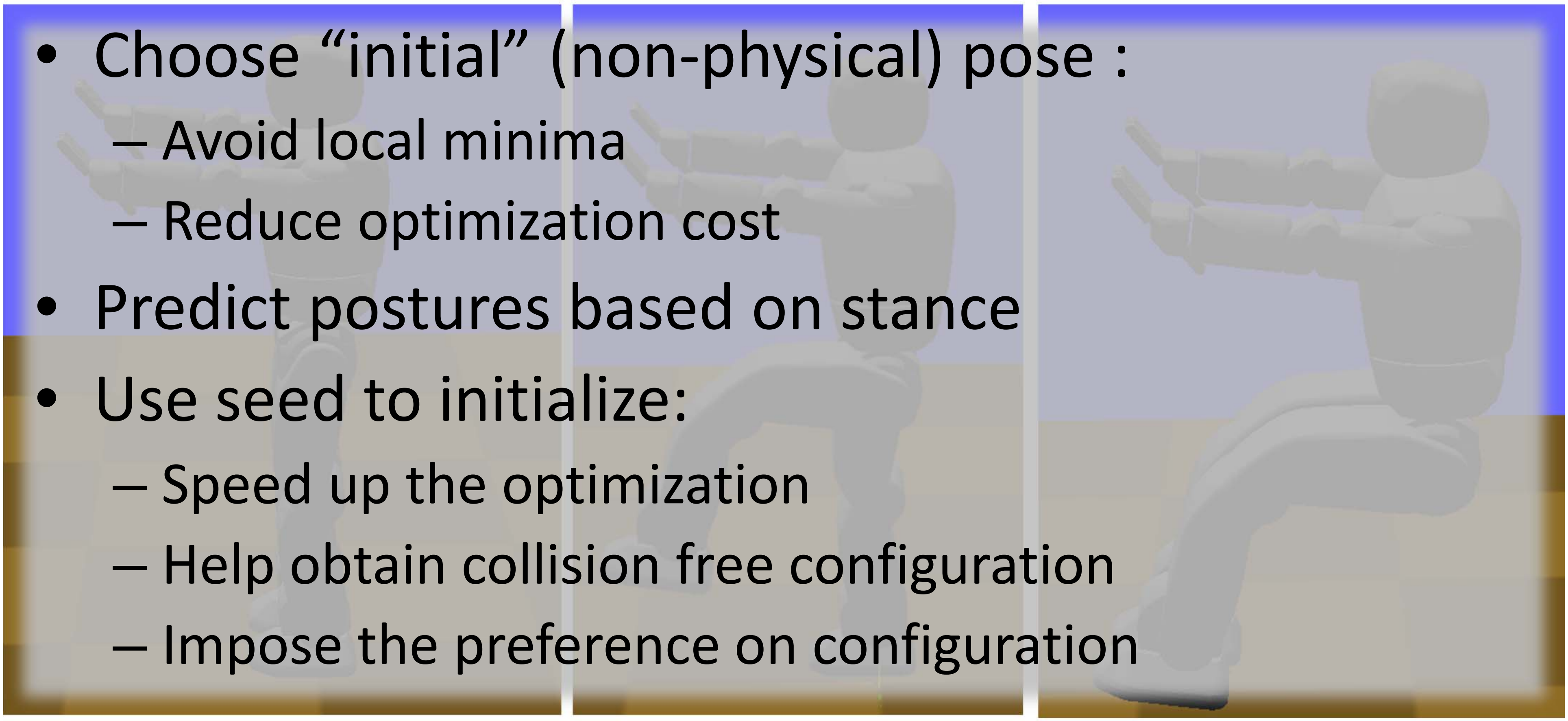
Find Feasible Configuration

- Input: Environment, existing holds $\mathbf{h_1}..\mathbf{h_3}$, desired hold $\mathbf{h_d}$
- Problem Formulation - Find q such that:
  - Contacts: desired position and rotation of links in $(\mathbf{h_1},\mathbf{h_2},\mathbf{h_3},\mathbf{h_d})$.
  - Within joint limits: $\mathbf{q} \in [\mathbf{q}_{\min}, \mathbf{q}_{\max}]$
  - Collision free: $\mathbf{C(q) = 0}$
  - No Self-Collision: $\mathbf{SC(q) = 0}$
  - Stable under gravity: $\mathbf{COM(q)} \in \mathrm{SP}(\mathrm{h}_1,\mathrm{h}_2,\mathrm{h}_3)$
- Strategy
  - **IK** based on constrained optimization

1. **Initialize** with a good start (seed configuration)
2. **Retract** if colliding slightly with ladder
3. **Perturb** in a growing neighborhood of seed

Seed Aided Initialization

- Choose "initial" (non-physical) pose :
  - Avoid local minima
  - Reduce optimization cost
- Predict postures based on stance
- Use seed to initialize:
  - Speed up the optimization
  - Help obtain collision free configuration
  - Impose the preference on configuration



Left: placeHands   Middle: liftLFoot   Right: liftRFoot

Algorithm for Finding q

- for i = 0, 1, 2, …, n:

  $q_{init} = q_{seed} + \text{perturb}(i)$

  if find q from IK solver starting from q_{init}:

  - if no self-collision and no environment collision and stable:

      return q

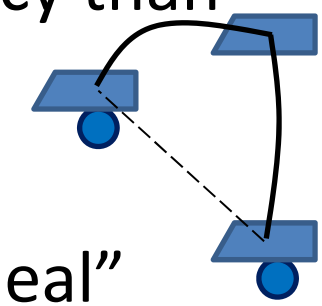
  - if no self-collision and has environment collision and stable:

      if retract(q) succeeds, return q

- perturb(i) function adjusts perturbation radius in joint space i*c for some constant c

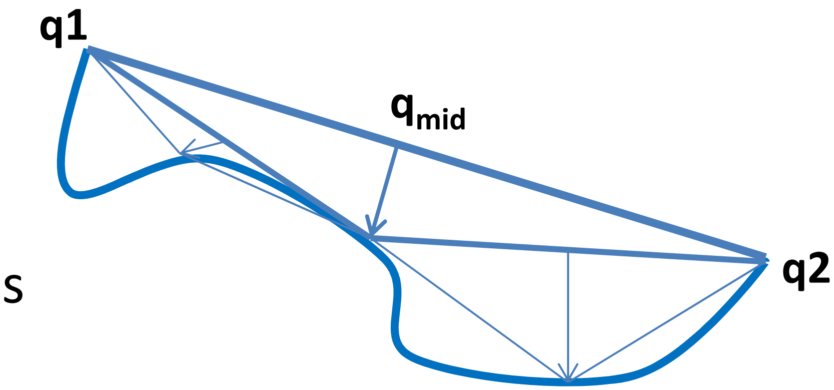
Connecting Path

- Challenge
  - Collision avoidance
  - Other fixed links should remain in contact
  - Natural looking actions, less redundancy than randomized planners



- Our method
  - Draw intermediate waypoints from "ideal" waypoint set
  - Interpolate in contact space, not joint space

Contact Space Interpolation



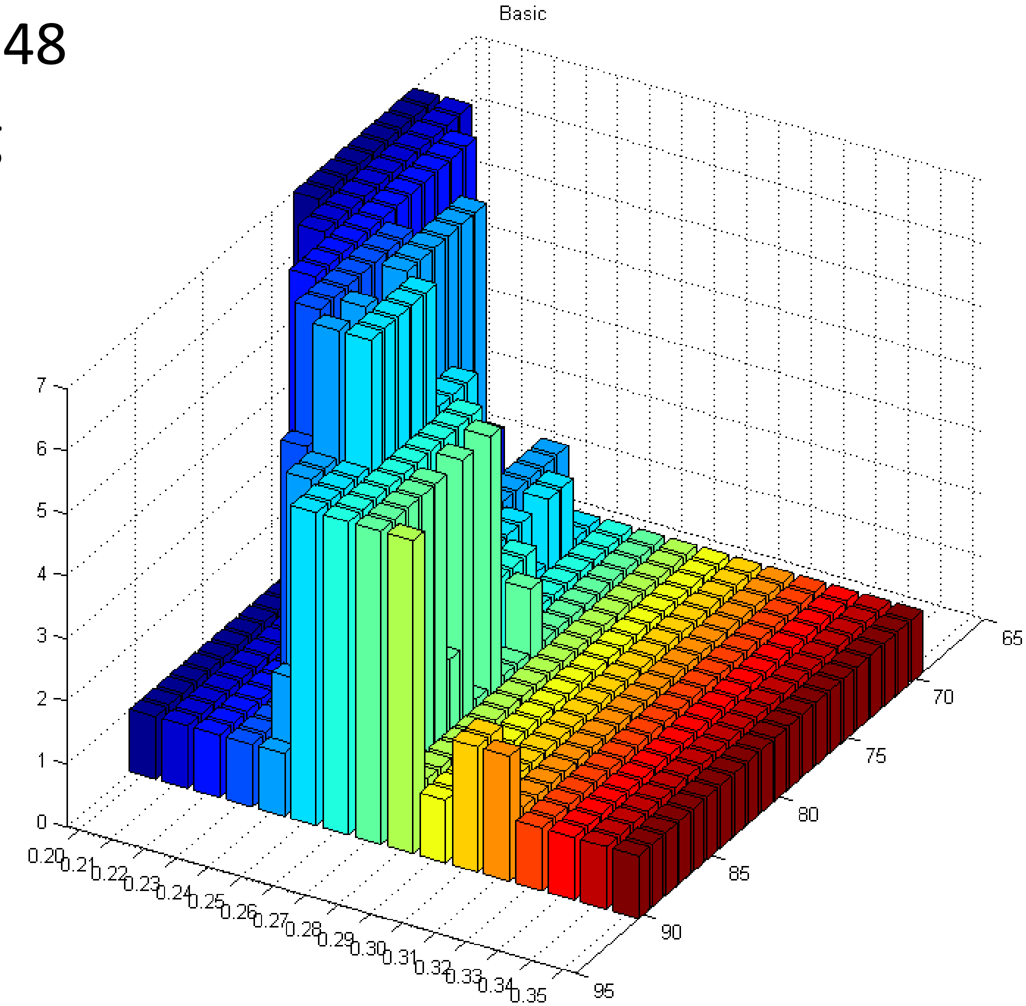
- Contact space
  - Specified by contacts
  - Subspace of joint space
  - Nullspace of contact constraints
- Recursive Interpolation
  - Linearly interpolate midpoint between q1 and q2 in joint space
  - Project from joint space to contact space
  - Repeat until desired motion resolution is reached
- Projection function
  - IK constraints are from fixed links
  - Solve IK to obtain projection point on contact space

Ladder Batch Testing

- Ladder specifications
  - Slope: 70° – 90°
  - Vertical spacing: 20 cm – 35 cm
- Apply all 7 motion primitives for each ladder
  - Kinematically feasible: no collision
  - Stable: COM within support polygon
- Intel i-7 with 4GB RAM; cutoff time: 60 seconds

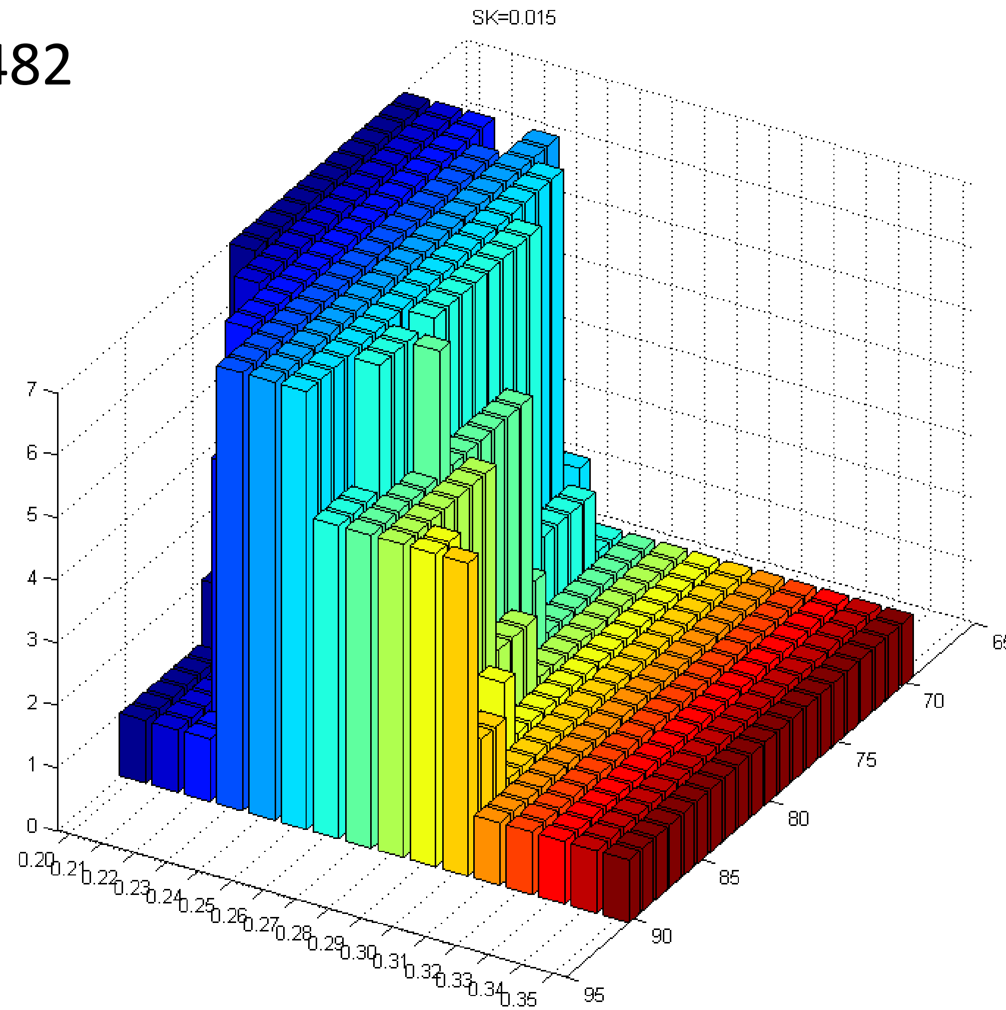
Original Hubo+ Model

- Overall success rate= 0.1548
- Success rate for mounting ladder only = 0.2530



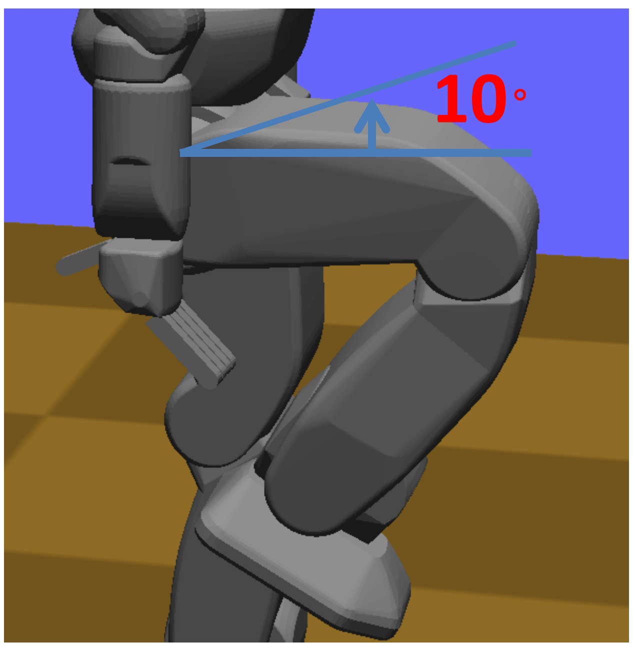
Shrink Knee Joints

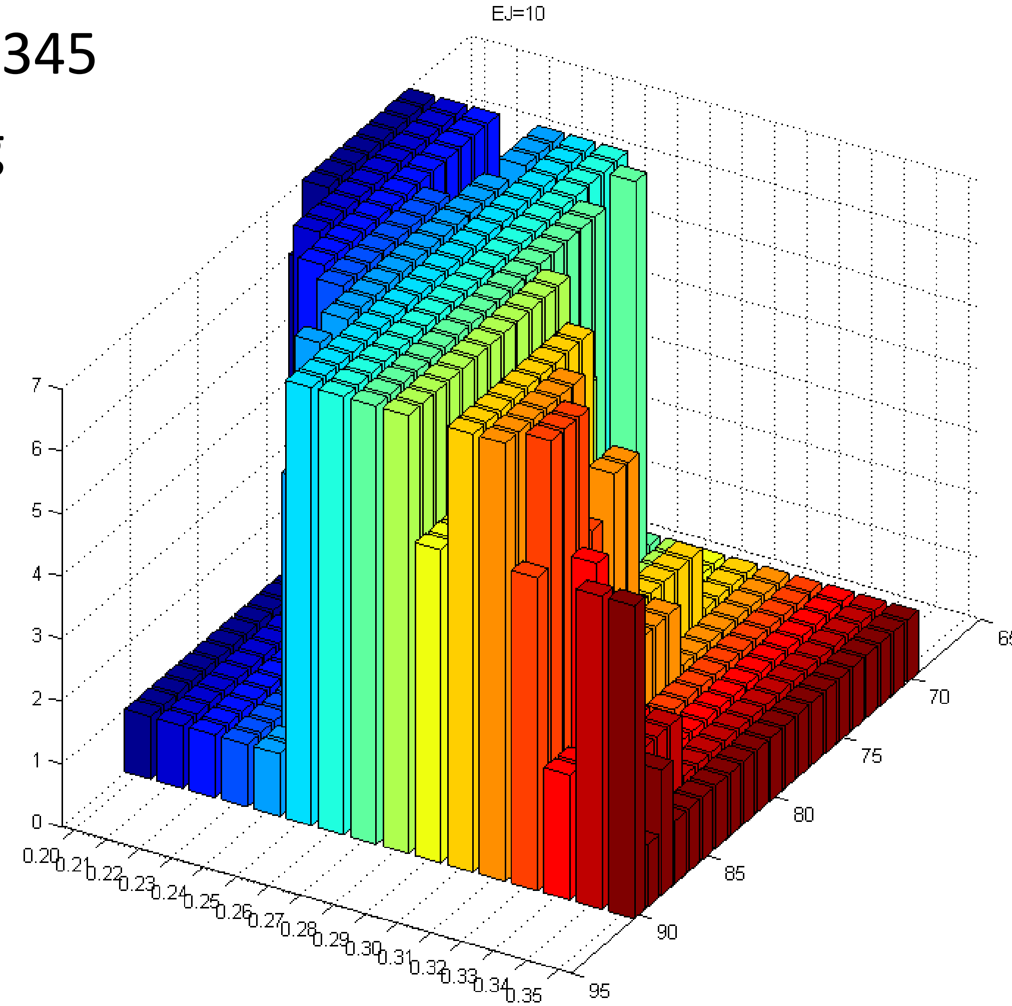
- Overall success rate = 0.3482
- Success rate for mounting ladder only = 0.4286



Enlarge Leg Joints Limits

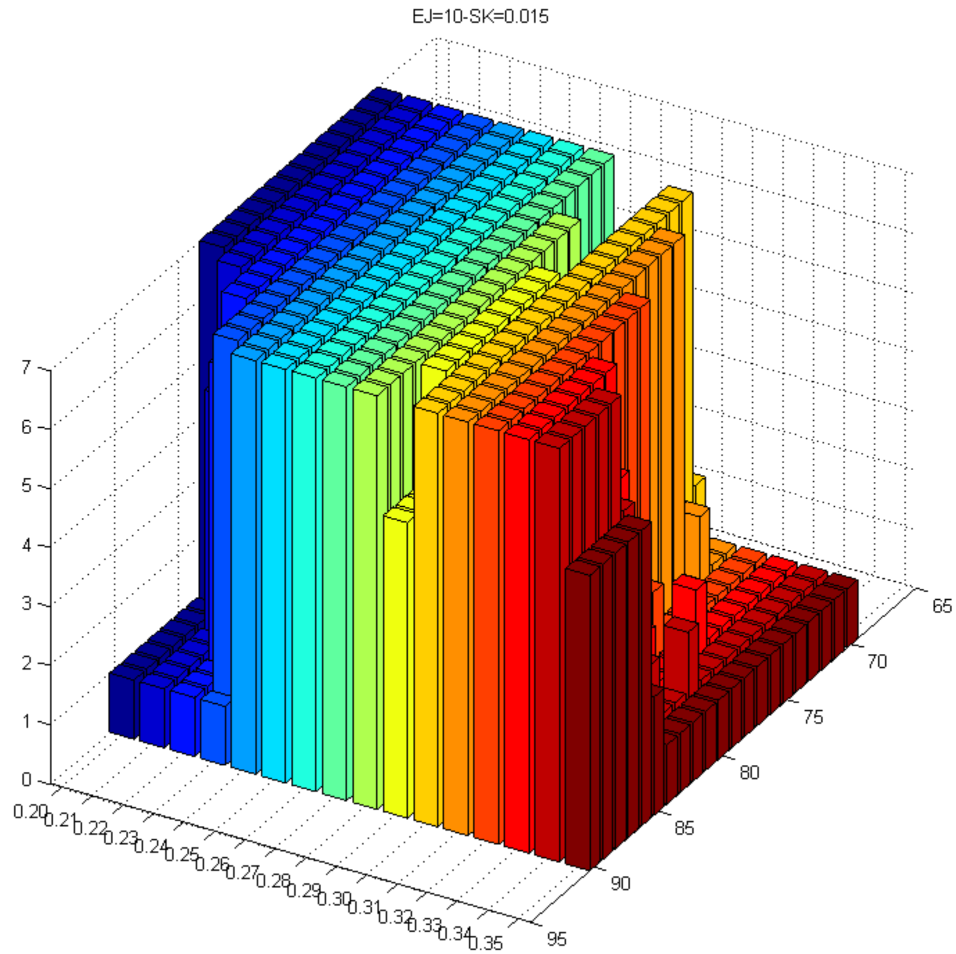
- Overall success rate = 0.4345
- Success rate for mounting ladder only = 0.5000





With Both Modifications

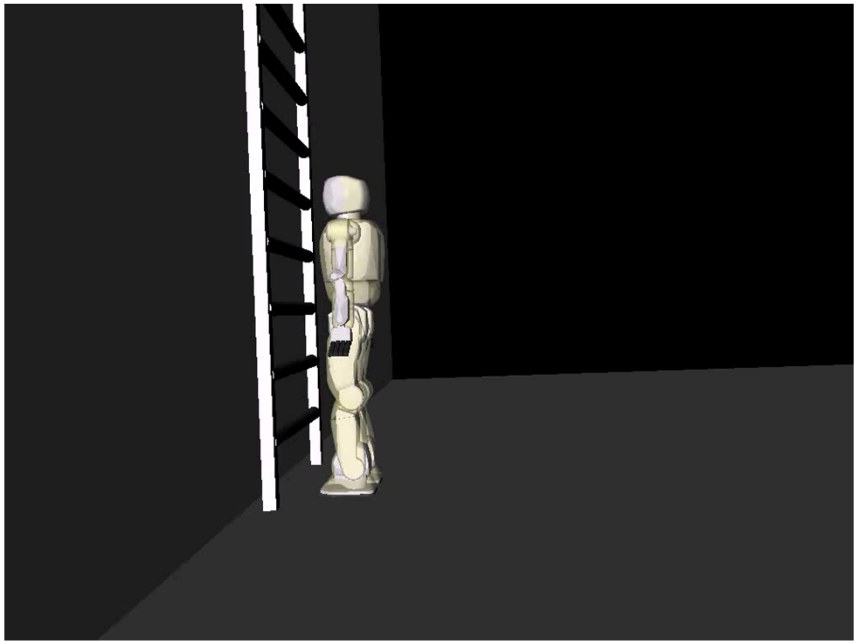
- Overall success rate = 0.7024
- Success rate for mounting ladder only = 0.7381

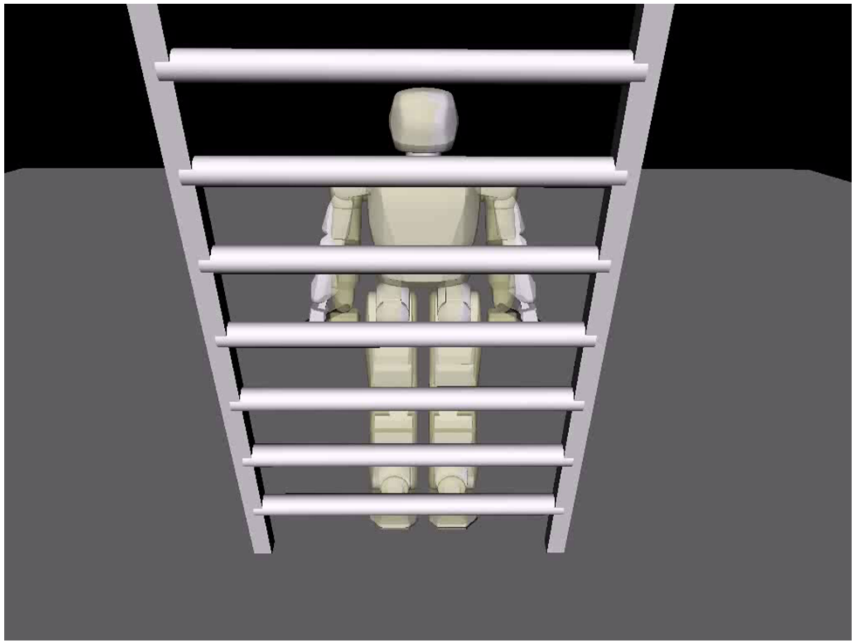


Validation Strategy

- Initial experiments to eliminate obvious gaps between environments
  - Ladder rung size
  - Initial position of robot
- Identify baseline finger properties that reproduce real behavior within limits of ODE
- Batch of simulations with various ladder shapes given “optimistic” grip strength
  - Stock hubo limits and leg size
  - No-Shell model’s thinner limbs
  - Expanded joint limits corresponding to no-shell model

First Simulation Results





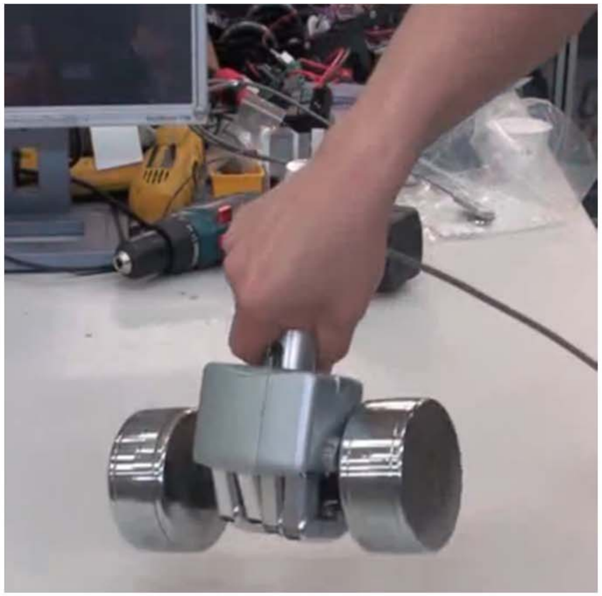
90º ladder reduces swinging room for arms

6cm Thick rungs drastically reduce available grip force

Simulation settings

Robot: rlhuboplus.noshell.robot.xml (expanded limits, no body shells)
Time step: 0.0005sec
Friction coefficient (u): 1
QuickStep iterations: 20
Trajectory time step: 0.05sec (5x slowed from planned motion)

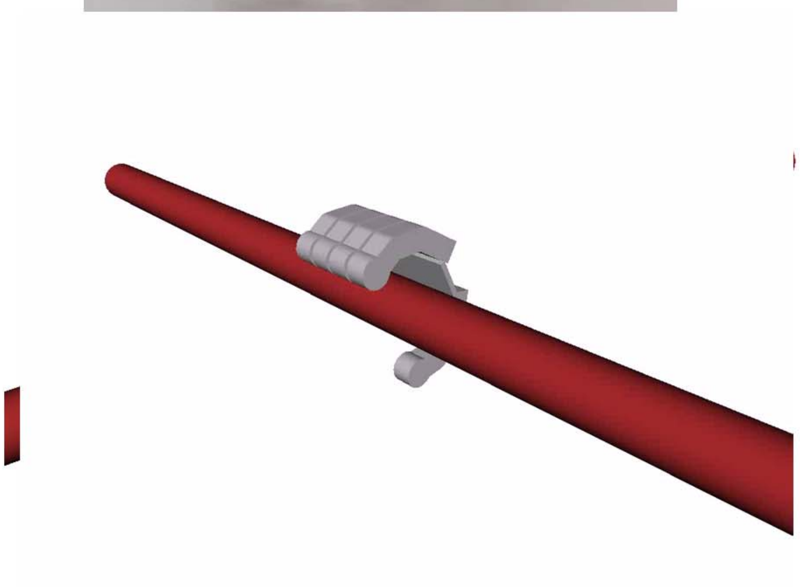
Quick Grasp Force Validation



- Assumptions / Setup
  - Servo controller contributes minimal torque (<.1 Nm) to grasp
  - Can control open-loop of finger joints
  - Grasp a 10b (**4.5kg**) weight
- Process and results
  - Max required grip torque was **1.6Nm** with mu=1.0 (erp=.5,cfm=0.00001)

Knuckle	1	2	3
Thumb	1.6Nm	.8Nm	.4Nm
Fingers	.8Nm	.4Nm	.25Nm

- Python script adds joint torque in addition to velocity motor



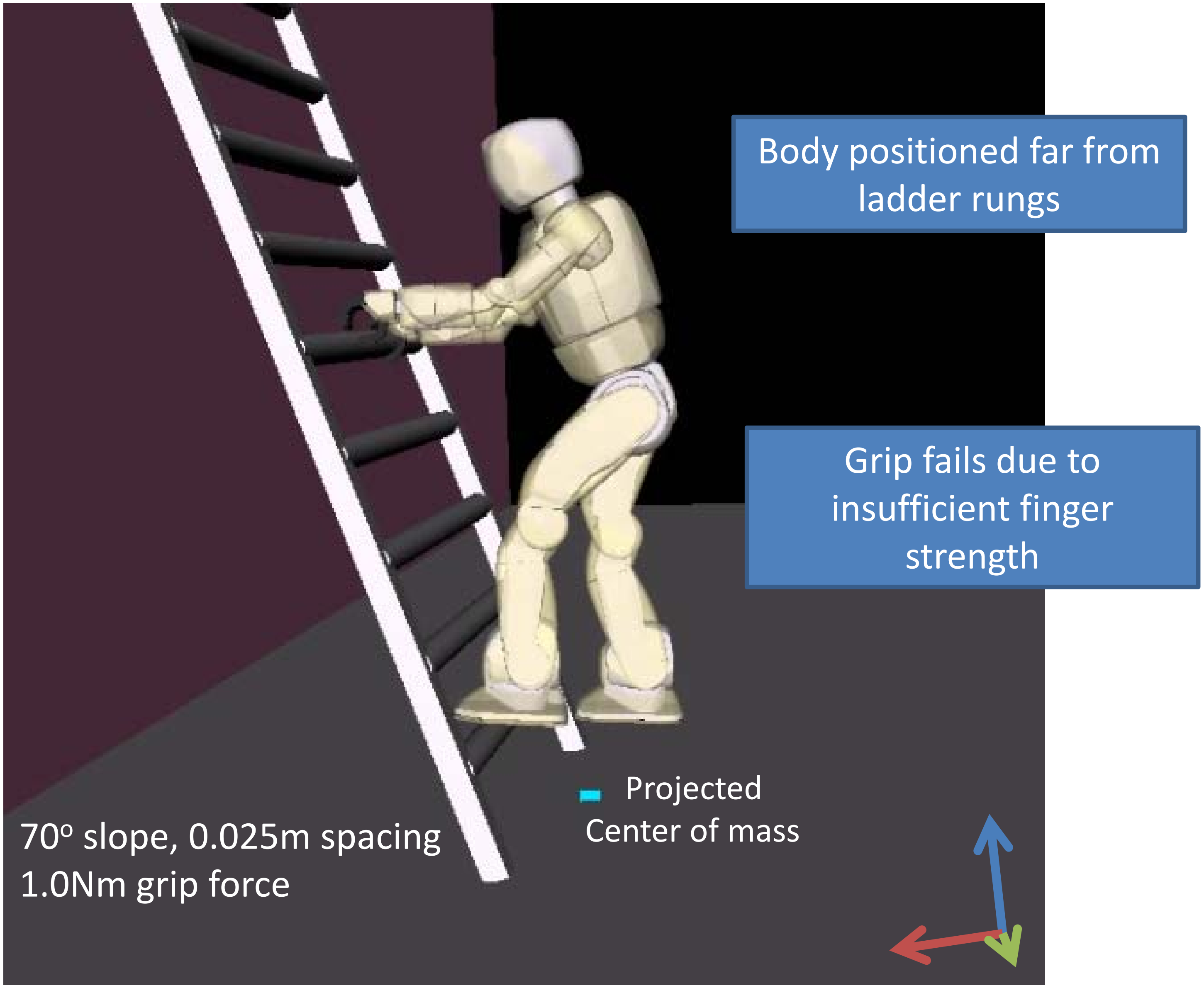
Simulation Results

TABLE I. PREDICTED SUCCESSES OF SELECT CASES WITH A STOCK HUBO-II+ AND THE MODIFICATIONS RECOMMENDED IN OUR MOTION PLANNER.

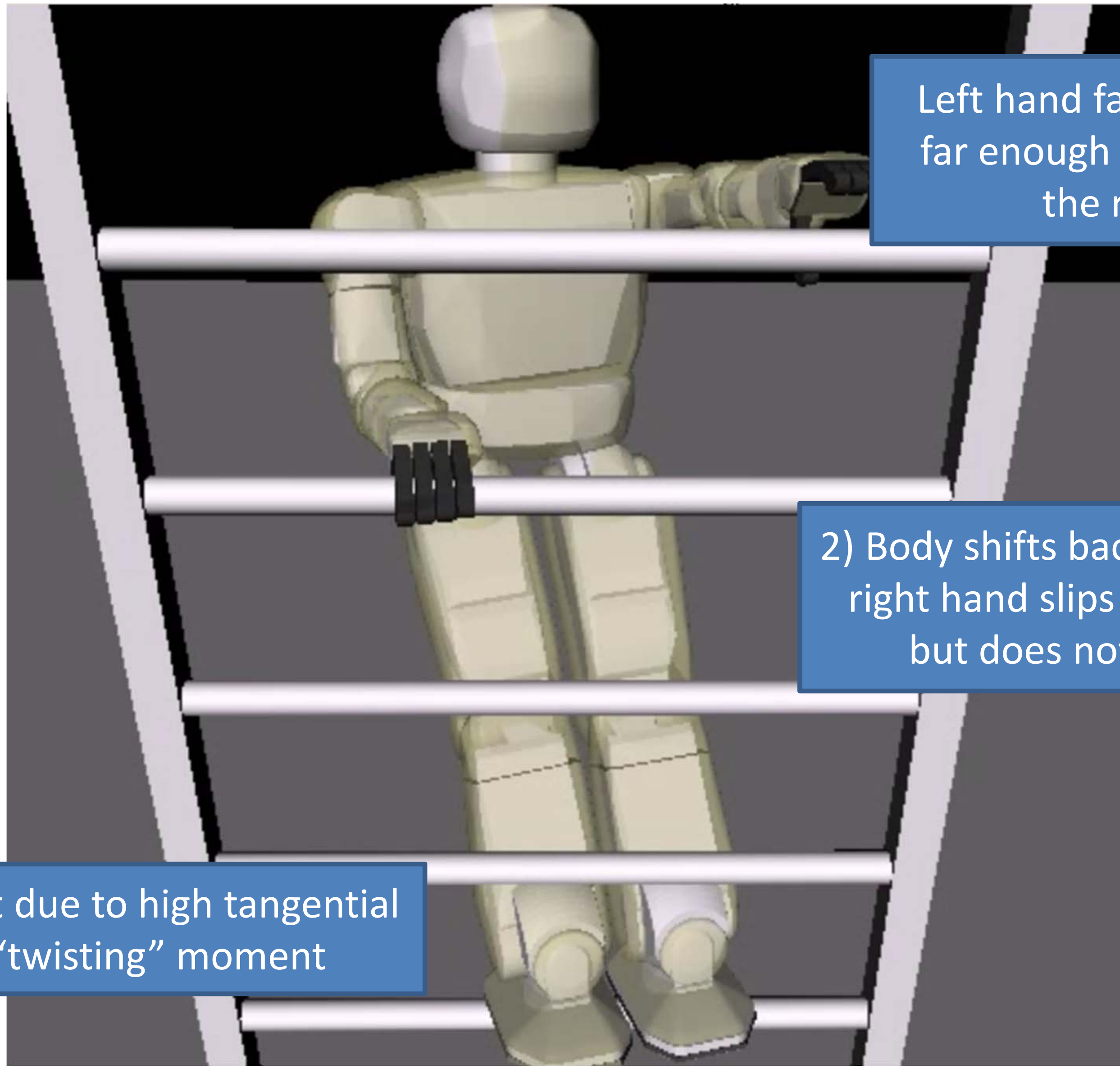
		Prediction		Result	
Angle	Spacing	Stock	Modified	Stock	Modified
70°	20 cm	7	7	2	7
70°	25 cm	2	7	2	5
75°	22 cm	7	7	2	5
75°	25 cm	2	7	2	5
80°	25 cm	7	7	2	5
80°	30 cm	2	7	2	5
85°	25 cm	7	7	2	3
85°	30 cm	2	7	2	3
90°	25 cm	7	7	0	0
90°	32 cm	2	7	0	0

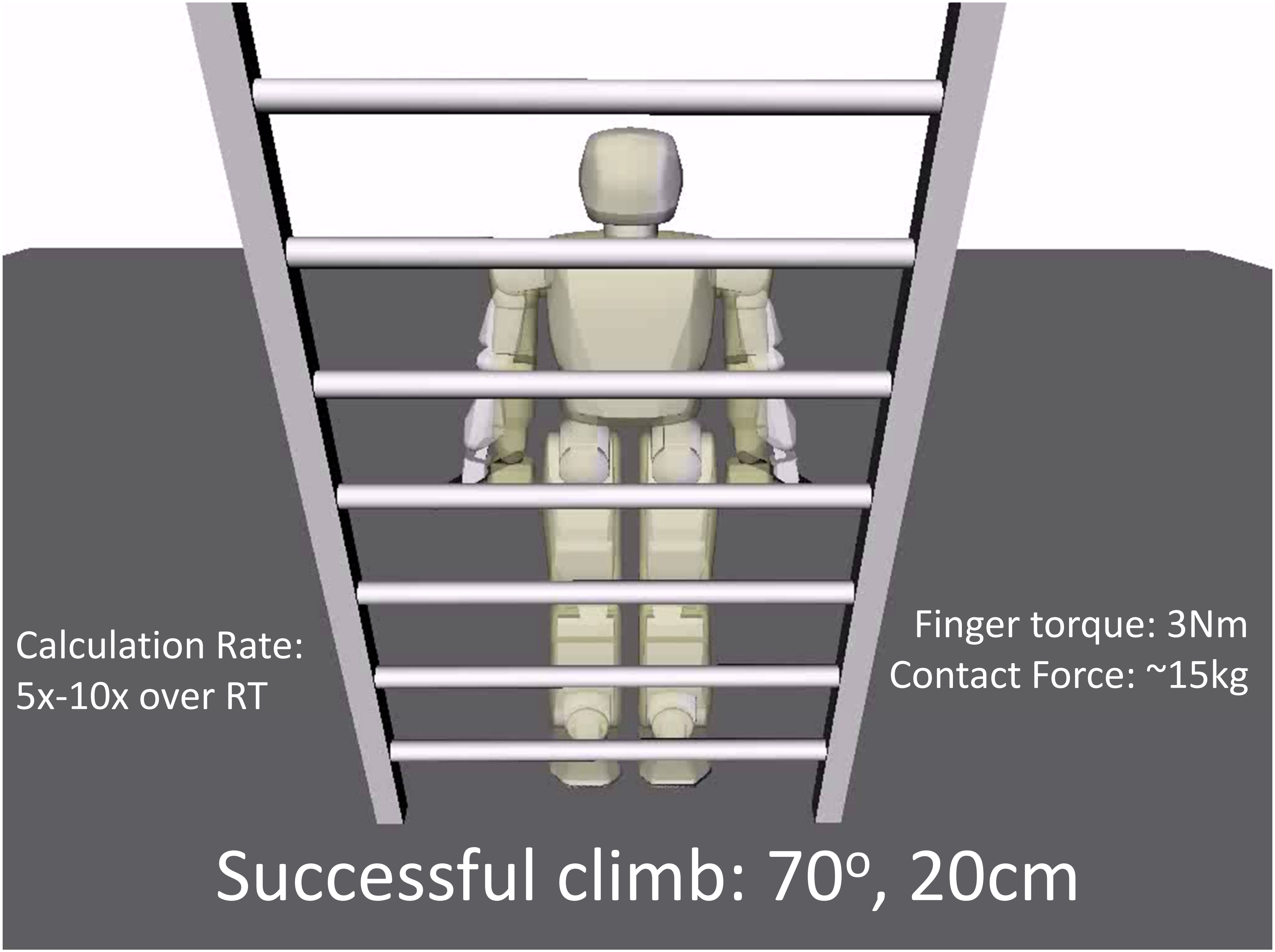
1) OpenHubo was able to climb onto ladders of slope <= 80°
2) Steeper ladders failed regardless of improvements
3) Only a combination of increased joint limits and thinner legs succeeded in stepping up

Failure Modes (1)



Failure Modes (2)




Calculation Rate:
5x-10x over RT
Finger torque: 3Nm
Contact Force: ~15kg
Successful climb: 70º, 20cm

Future Work (Planning)

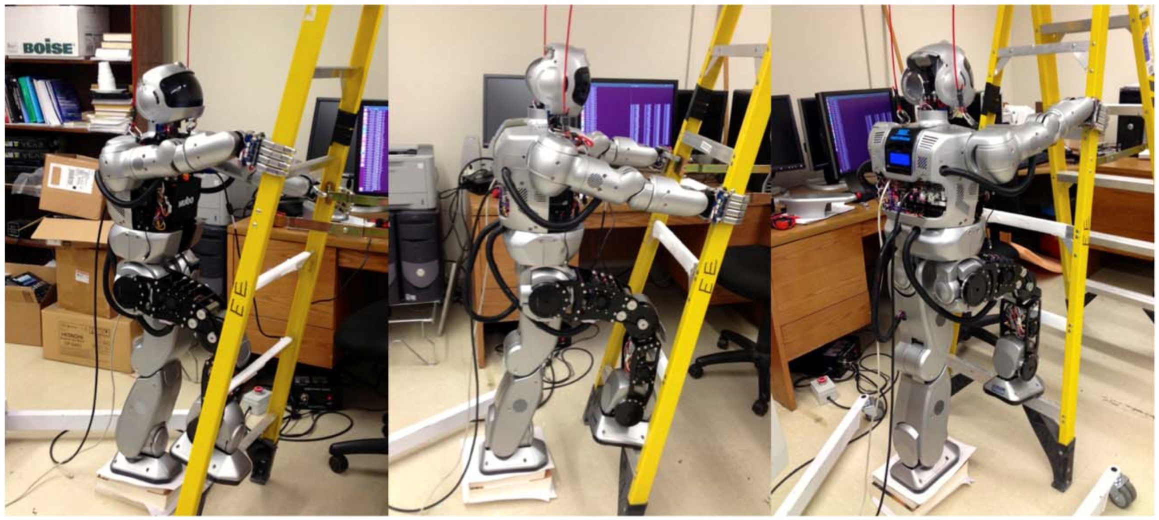
Possible improvements

- Estimate grip forces from pose and contacts
- More seed poses (bent elbows / knees) reduce required swing room
- Explicitly check stability in intermediate poses
- Friction at feet as additional optimization criteria
- Seed configurations with lower grip force

Future Work - Simulation

- Possible contact modeling improvements
  - Adjust ODE quickstep iteration limit
  - KrisLibrary
  - FCL + DART
- Physics Improvements
  - Reduced-density models
  - Open-loop torque control
  - Motor estimation for failure states (overvoltage, overtorque, “jam” error)

Hardware Considerations



- Thinner limbs with greater range of motion
- Increase grip and wrist strength
- Friction enhancement for hands / feet
  - Grooves / channels to “lock-in” to ladder surface
  - Grip surfaces
- “5 point” Harness for rigging Hubo during experiments
- In-place recovery (motor power-off preserves encoder values)

Questions?