OPTIMIZATION-BASED MOTION GENERATION FOR COMPLETING BUZZWIRE TASKS WITH THE REEM-C HUMANOID ROBOT

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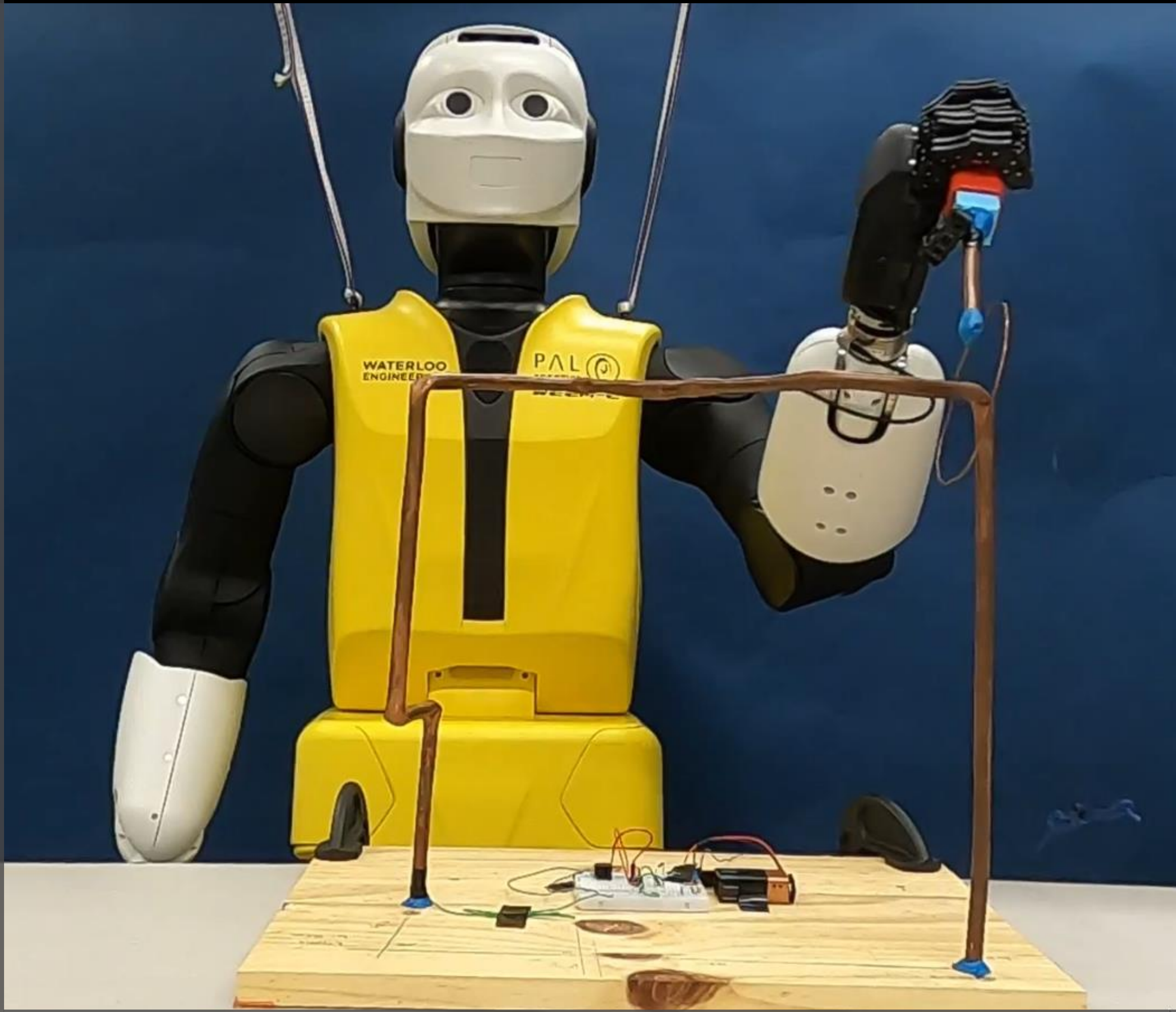

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Article

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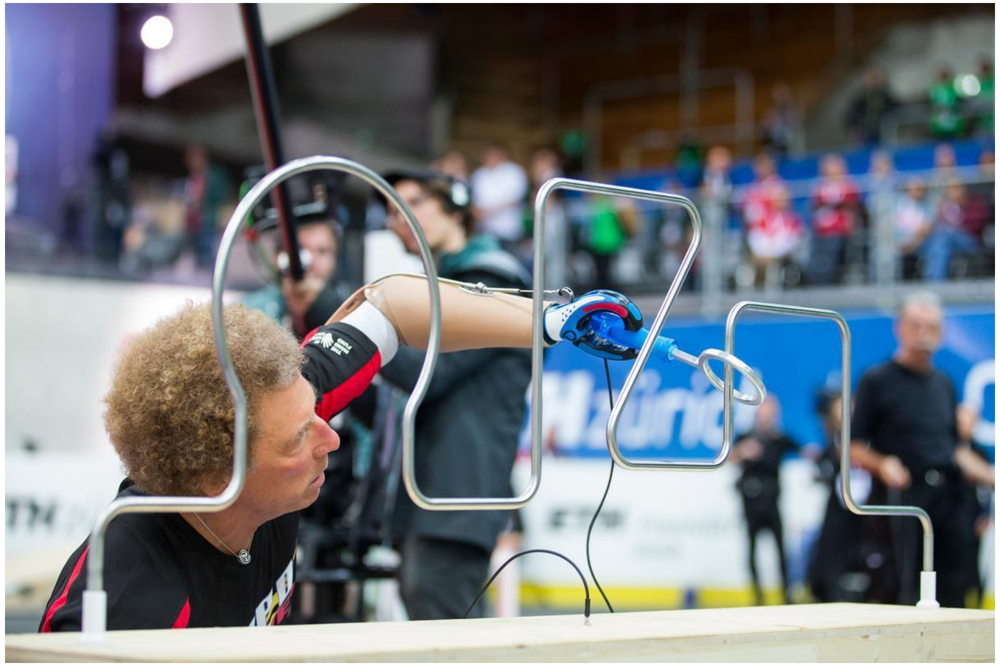
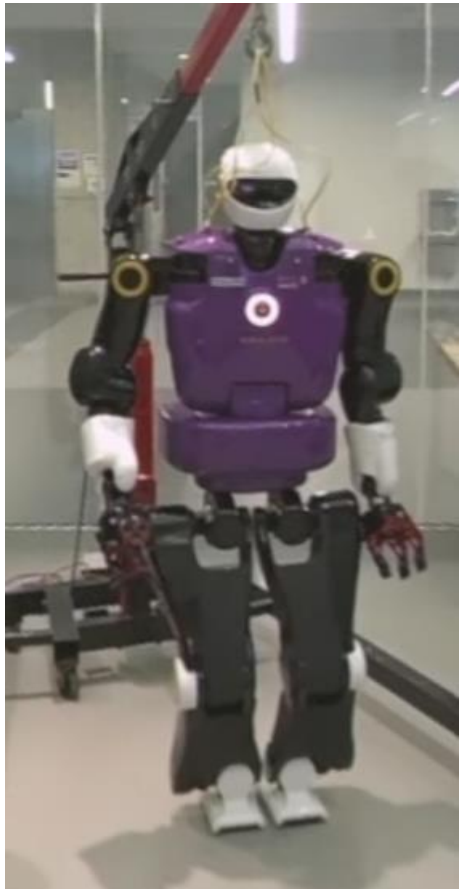
Overview of buzzwire task

- Description:
  1. Hold a conductive loop end-effector
  2. Traverse obstacle other without collisions
  3. Minimize time to completion



Application to humanoid

- Dexterity/agility benchmark
- Extensions to high precision tasks



Contribution

- Buzzwire on humanoid Reem-C robot
  - Formulation of OCP to generate valid trajectories
  - Evaluate on trajectories over three example obstacles
  - Examine discrepancy from running on hardware

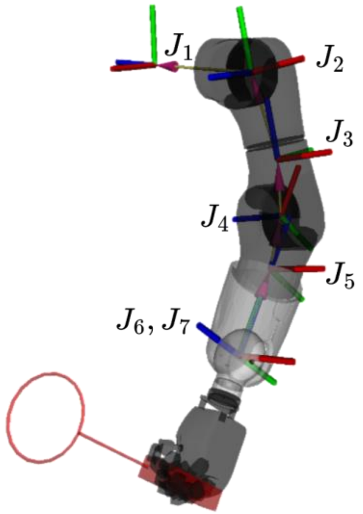
MATERIALS & SETUP

Humanoid

Obstacle construction & parameterization

Reem-C humanoid

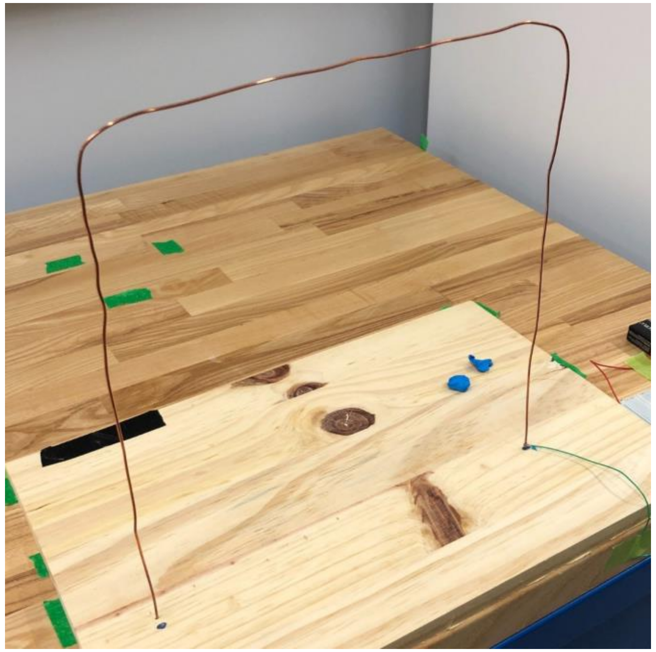
- Humanoid robot with 30 actuated joints.
- Using left arm for buzzwire (7-dof)
- Position/Velocity controller



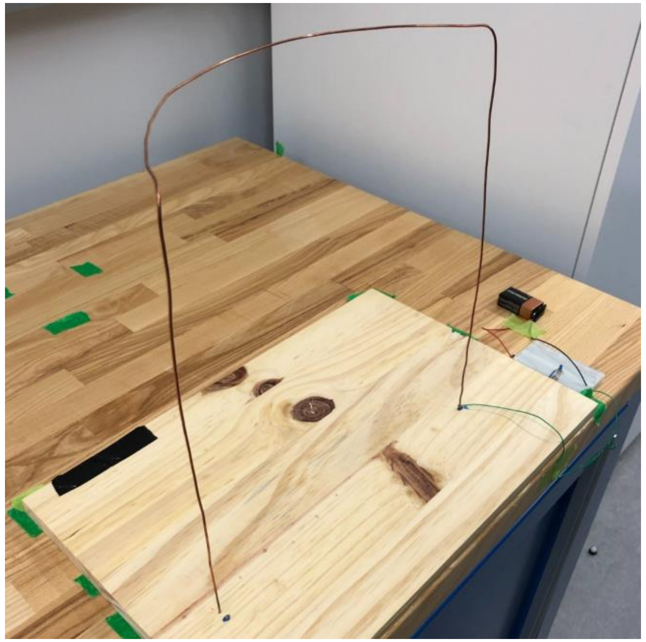
Obstacle

- Three obstacles formed from copper wire/tubing

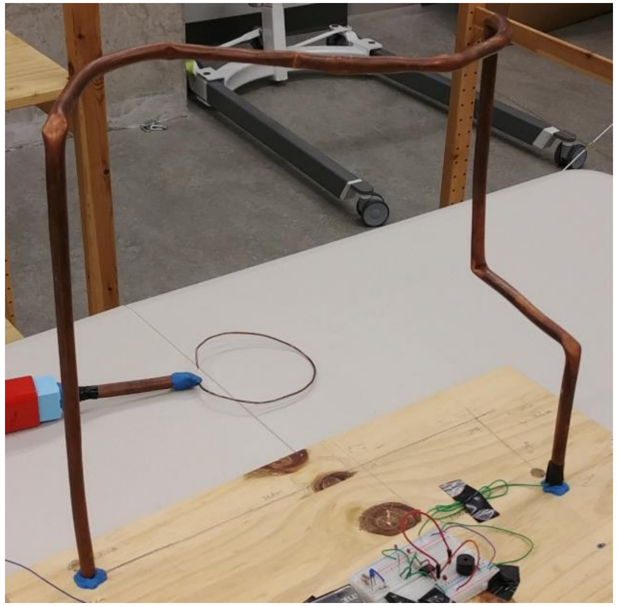
Obstacle-A



Obstacle-B

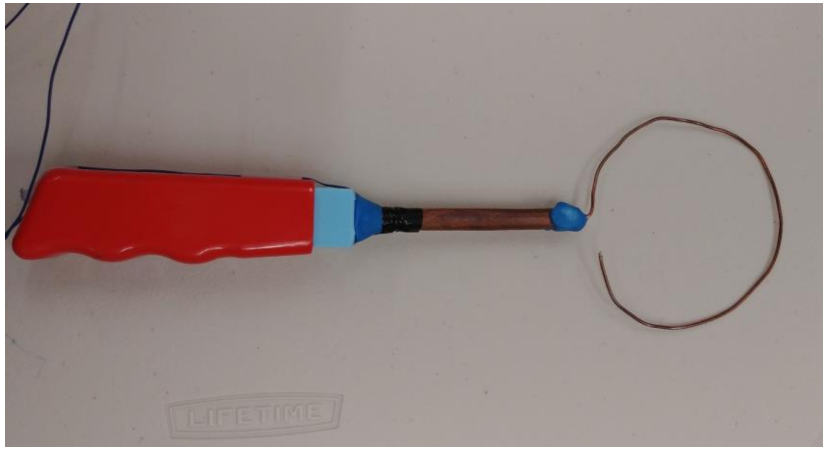


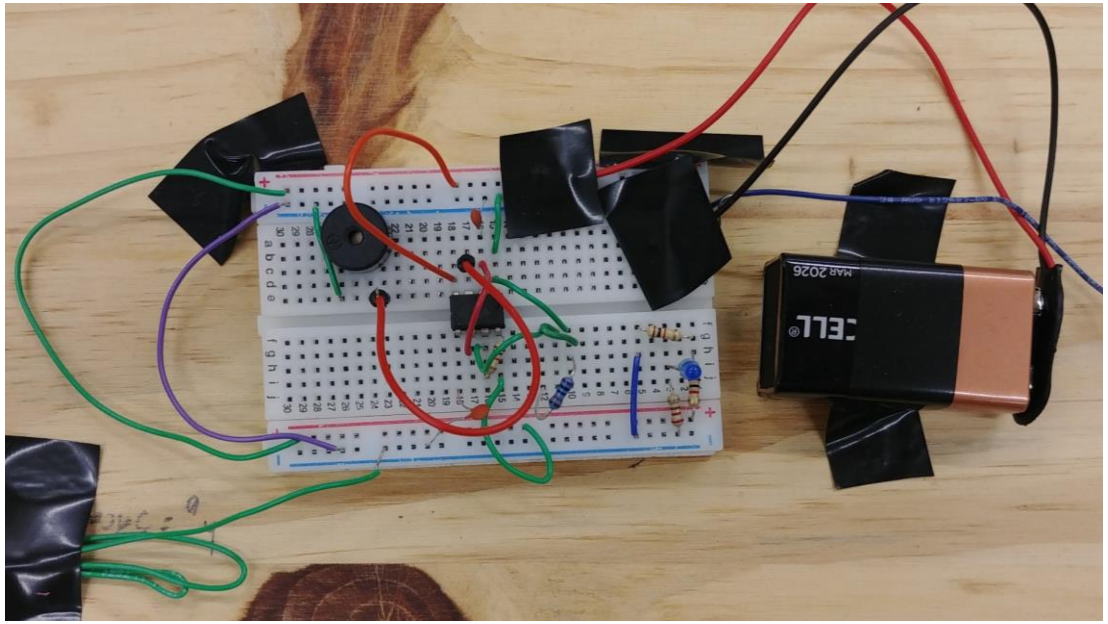
Obstacle-C



Obstacle wiring

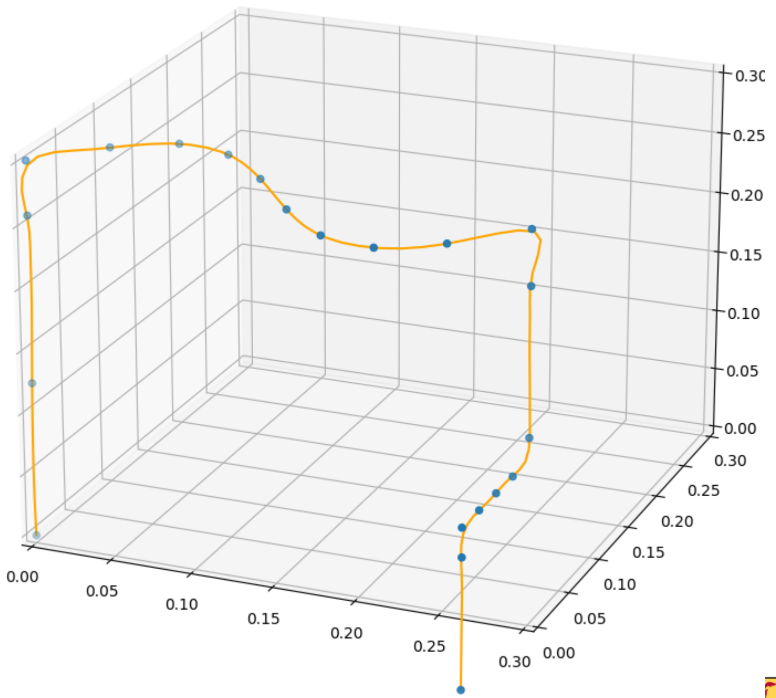
- Circular end-effector (5 cm radius)
- When closed, collision indicated with LED illumination and piezoelectric buzzer





Representation of Obstacle

- Select discrete 3D to represent obstacle
- Fit cubic spline parameterized by normalized arclength (β)
  - Start: $\beta = 0$, End: $\beta = 1$



METHODS

Optimal Control Problem

- Variables
- Objective function
- Problem constraints
- Discretization

$$\min \; f(x)$$
$$g(x) \leq 0$$
$$h(x) = 0$$

State variables

- $q(t)$ – Joint position
- $\beta(t)$ – Obstacle target
- $\dot{q}(t)$ – Joint velocity
- $\dot{\beta}(t)$ – Obstacle target velocity

Control variables

- $\ddot{\beta}(t)$ - Obstacle target acceleration
- $\ddot{q}(t)$ – Joint acceleration

Free variables

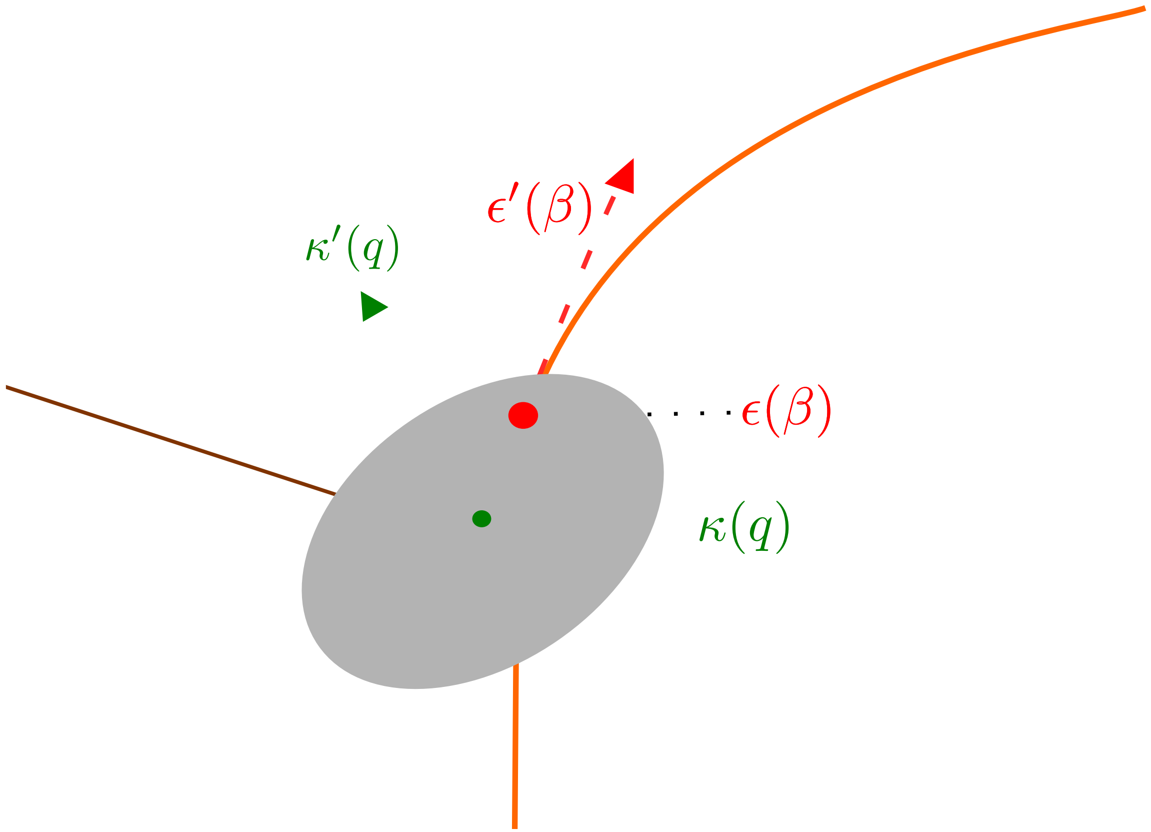
- t_f – total time

State equations

$$\ddot{q} = \frac{\dot{q}}{dt}, \dot{q} = \frac{q}{dt}, \ddot{\beta} = \frac{\dot{\beta}}{dt}, \dot{\beta} = \frac{\beta}{dt}$$

Task space

- $\epsilon(\beta)$ - Obstacle position
- $\epsilon'(\beta)$ - Obstacle tangeant
- $\kappa(q)$ - End effector position
- $\kappa'(q)$ - End effector normal



Problem objective

- Considerations:

$$\min_{\ddot{q},\ddot{\beta}} \left\{ \overbrace{t_f}^{\text{Trajectory time}} + \int_0^{t_f} \left[\overbrace{\underline{\alpha} ||\kappa(q(t)) - \epsilon(\beta(t))||_2}^{\text{Distance from obstacle}} - \overbrace{\underline{\nu} \kappa'(q(t))^\top \epsilon'(\beta(t)) \right] dt}^{\text{Orientation from obstacle}} \right\}$$

Weights

Problem Constraints

- Three categories of constraints

1. Limits

$$q^{\min} < q(t) < q^{\max}$$
$$\dot{q}^{\min} < \dot{q}(t) < \dot{q}^{\max}$$
$$\ddot{q}^{\min} < \ddot{q}(t) < \ddot{q}^{\max}$$

2. Start/Termination

$$\dot{q}(0) = 0$$
$$\dot{q}(t_f) = 0$$
$$\beta(0) = 0$$
$$\beta(t_f) = 1$$
$$\dot{\beta}(t) \geq 0.0$$

Problem constraints

3. Collision

$\delta = 10^{-4}$

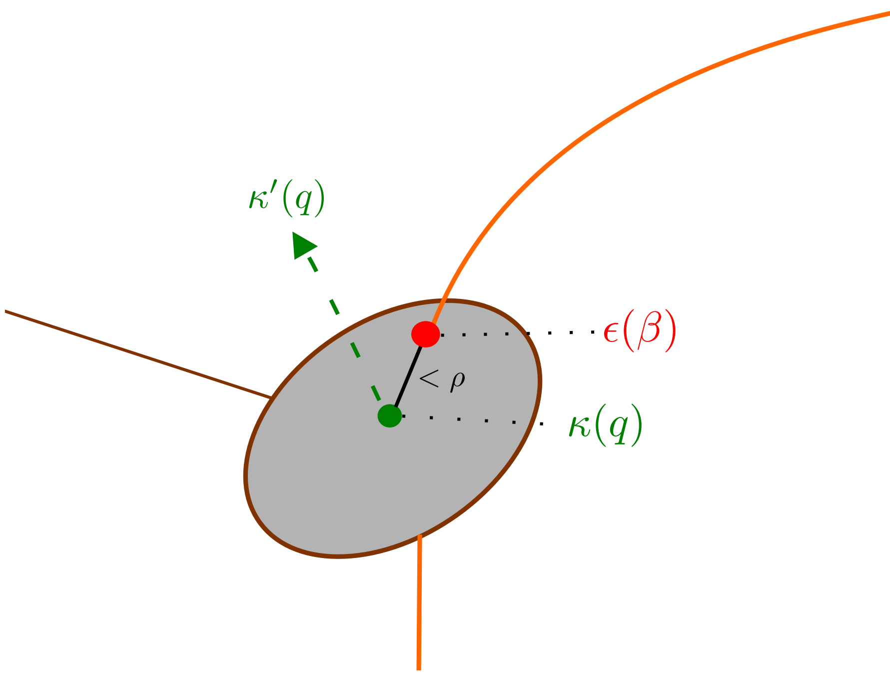
Coplanar constraint: $$-\delta < \kappa'(q)^\top(\kappa(q) - \epsilon(\beta)) < \delta$$

$\rho = 1$ cm

Euclidean constraint: $$||\kappa(q(t)) - \epsilon(\beta(t))||_2 < \rho$$

$\mu = 0.55$

Orientation constraint: $$\kappa'(q(t))^\top \epsilon'(\beta(t)) > \mu$$



Multiple shooting

- Transform continuous OCP into discrete non-linear program (NLP)
  - N=100 discrete shooting nodes
- Discrete states $\{q_1, \dots, q_N\}, \{\dot{q}_1, \dots, \dot{q}_N\}$, etc.

Discretized Objective Function

$$t_f + \sum_{i=1}^{N} \left[\alpha ||\kappa(q_i) - \epsilon(\beta_i)||_2 - \nu \kappa'(q_i)^\top \epsilon'(\beta_i)\right]$$

Continuity Constraints

$$q_{i+1} = q_i + \dot{q}_i \Delta t + \frac{1}{2} \ddot{q}_i \Delta t^2$$

$$\dot{q}_{i+1} = \dot{q}_i + \ddot{q}_i \Delta t$$

$$\beta_{i+1} = \beta_i + \dot{\beta}_i \Delta t + \frac{1}{2} \ddot{\beta}_i \Delta t^2$$

$$\dot{\beta}_{i+1} = \dot{\beta}_i + \ddot{\beta}_i \Delta t$$

Software

- Multiple shooting problem modelled in RBDL-CasAdi
  - RBDL replacing floating point ops with CasAdi symbolic ops
  - Allows auto-differentiation of $\kappa(q)$ and $\kappa'(q)$
- IPOPT solver
  - Converges solutions in 15 (A), 25 (B), 42 (C) seconds.

RESULTS

Impact of parameter tuning

Trajectory examples

Hardware analysis

Trajectory generation

Select initial values
With $q = \kappa^{-1}(\epsilon(0))$

Choose α, ν

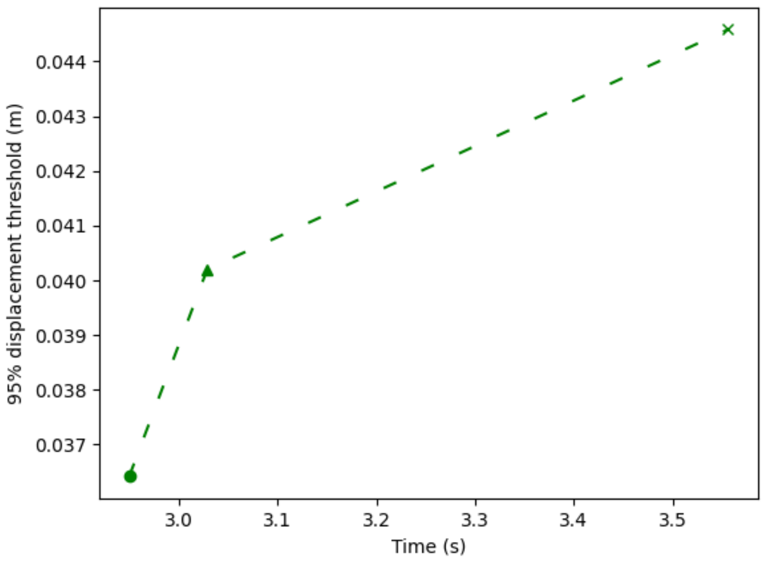
Solve NLP

Parameter trade-off

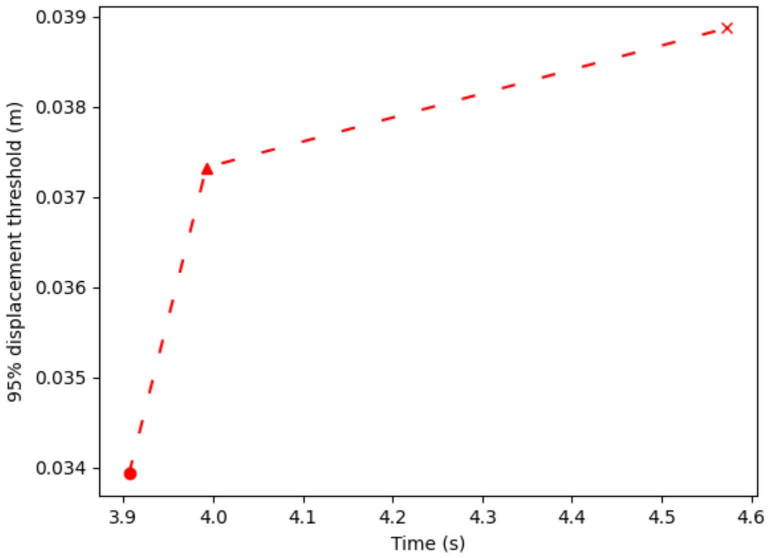
α- Euclidean penalty
ν- Orientation penality

- Time vs margin collision with three different parameter configurations
  - $(\alpha = 0, \nu = 0)$,$(\alpha = 30, \nu = 1)$,$(\alpha = 150, \nu = 5)$

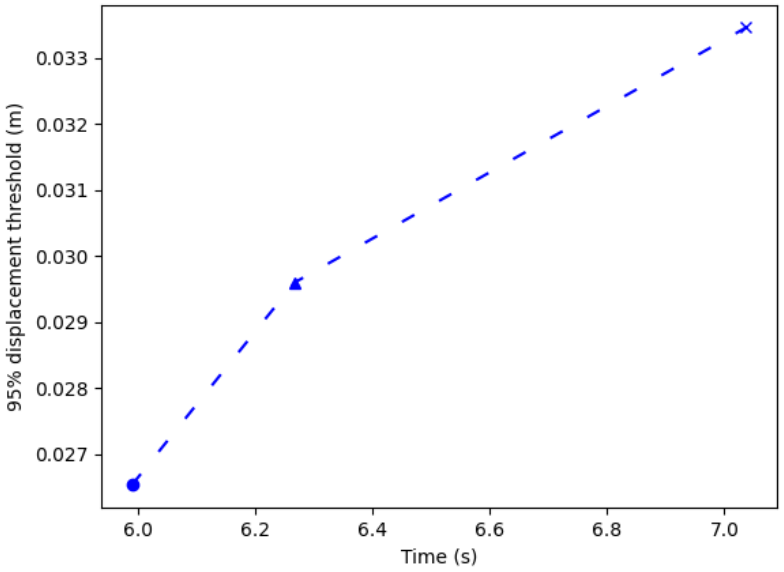
Obstacle-A



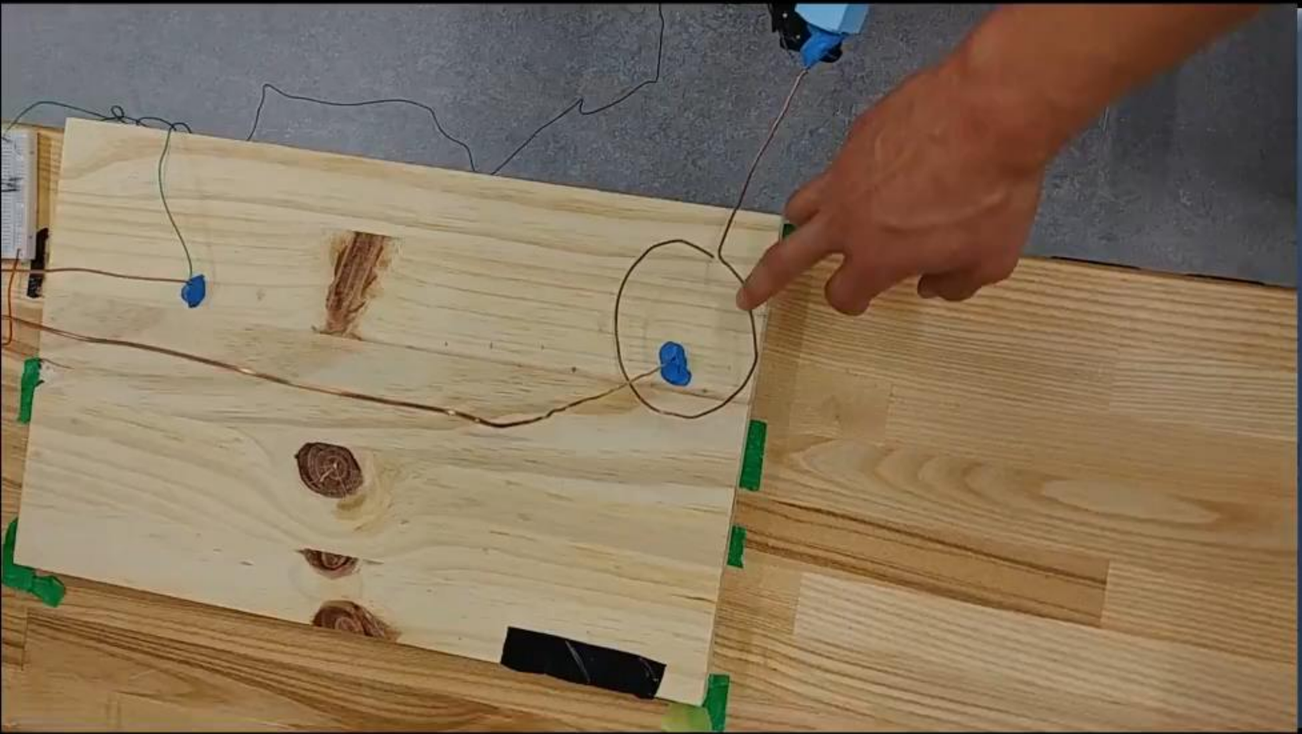
Obstacle-B

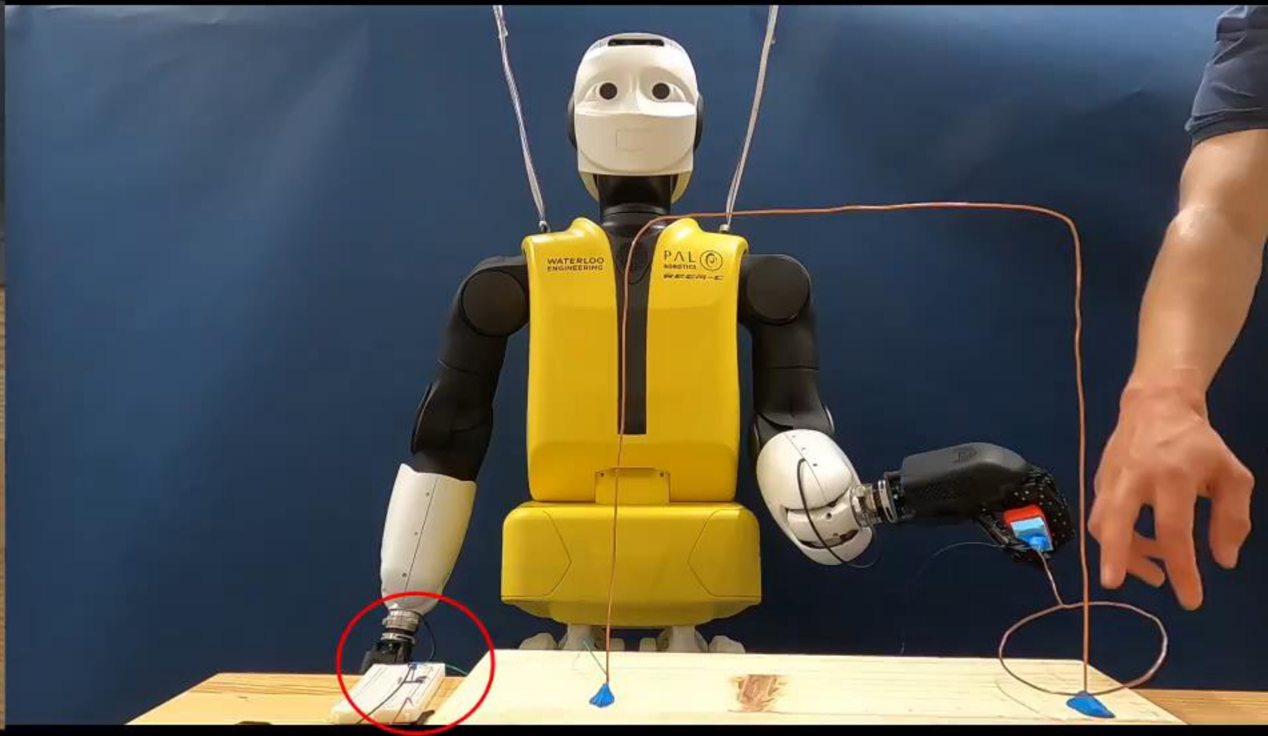


Obstacle-C



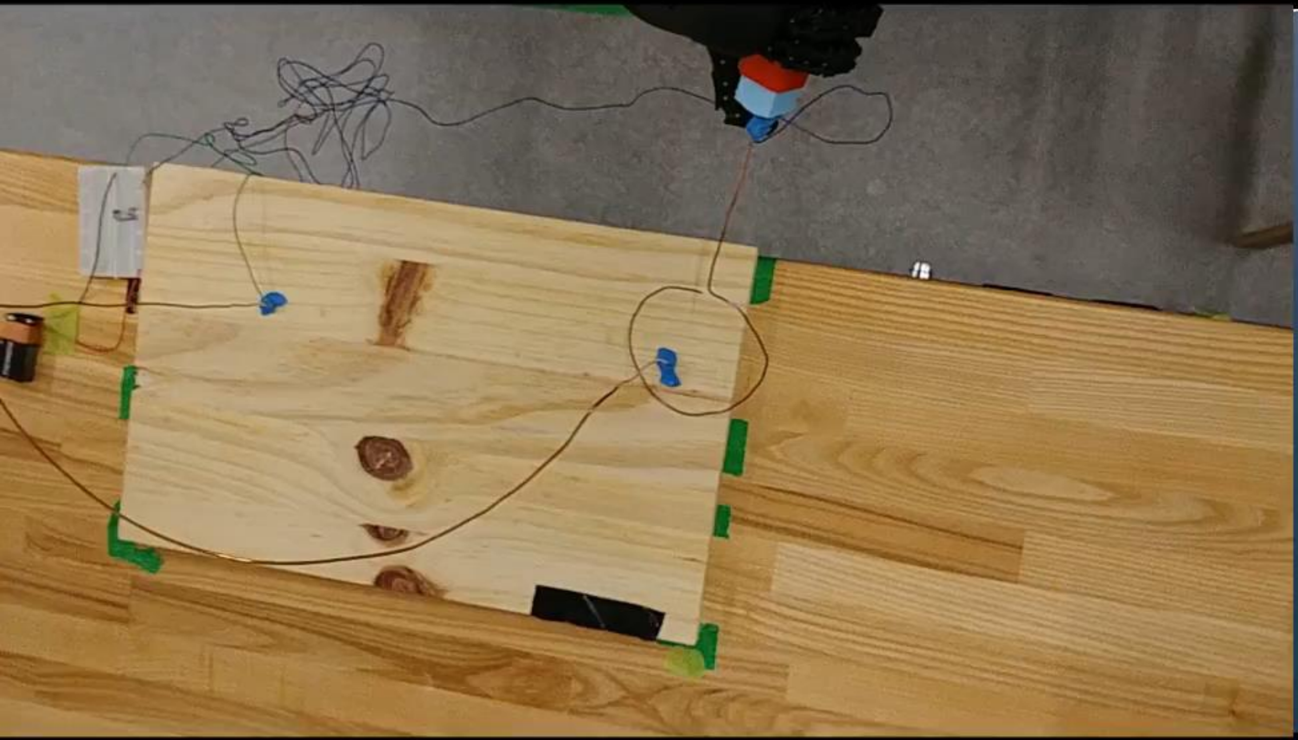
Obstacle-A

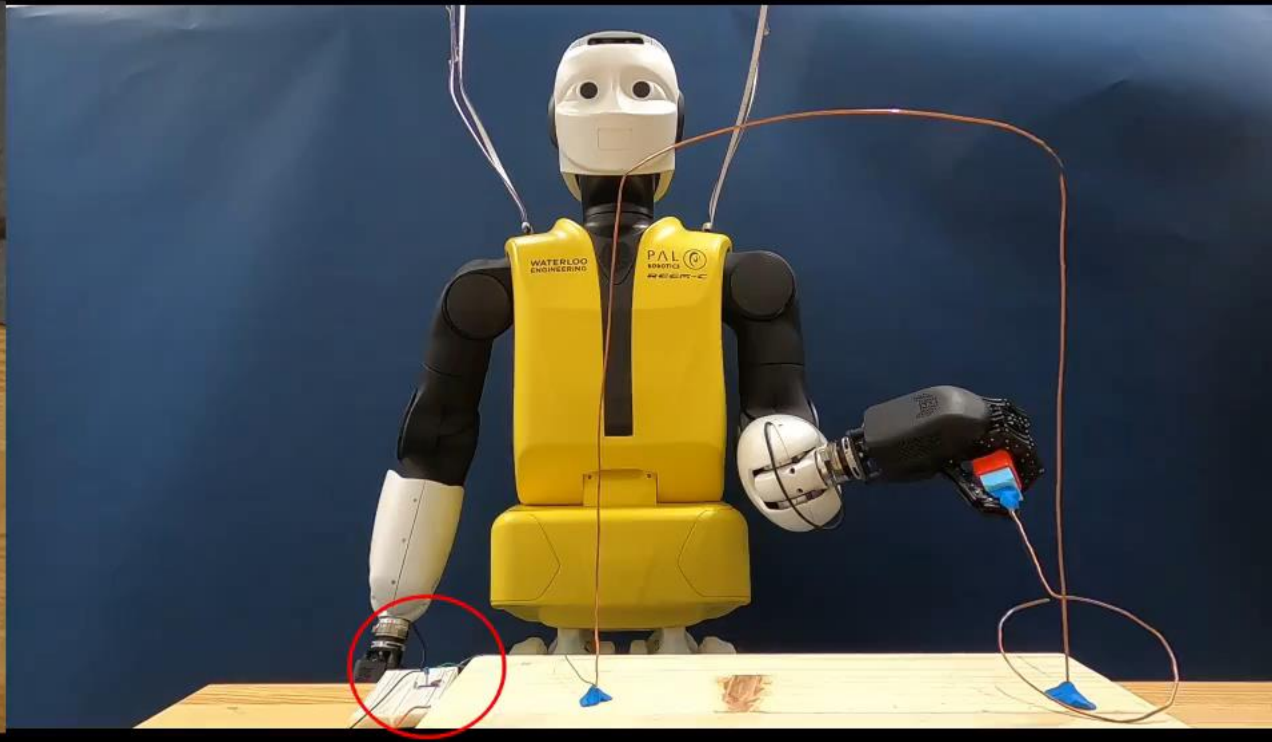




Verifying contact
circuit is live

Obstacle-B





Verifying contact
circuit is live

Obstacle-C

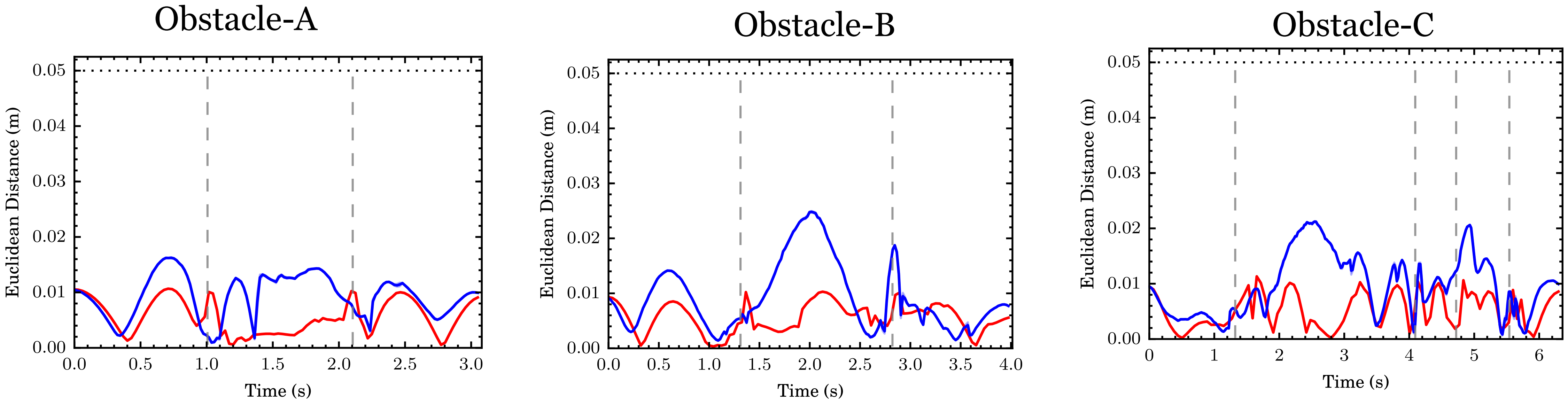
Hardware summary

- All trajectories could run without collisions
    - Careful positioning of base required.
- Some deviation between nominal and recorded trajectories.

Legend

Hardware

Nominal



FUTURE EXTENSIONS

Full body Motion

- Enable larger & more complex obstacles
- Exploit body momentum for faster trajectories

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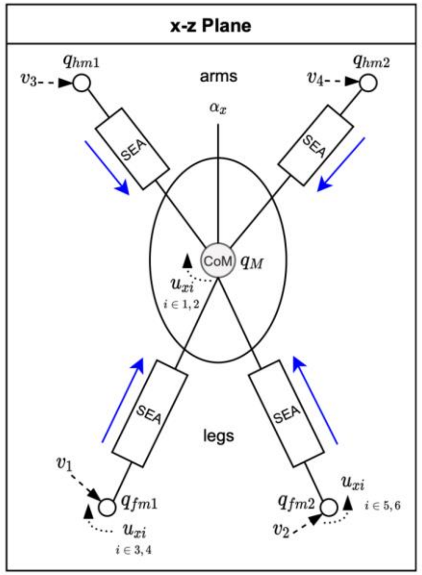
Challenges

- More DOF
  - Harder to solve computationally
  - Template models?
- Stability constraints
  - End-effector stabilization

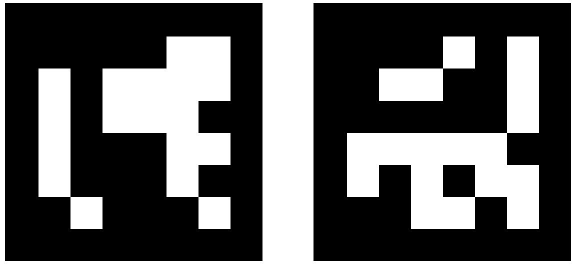


Solving trajectories online

- Traverse obstacles from arbitrary starting poses
- Generalize to unseen/unknown obstacles

Challenges

- Hard to visualize thin obstacles with current stereo/depth cameras
- Artificial visual tags (e.g., Aruco markers, AprilTags)
  - Error margin still very small (< 5cm)
  - Camera calibration and base estimation need to be very fine tuned



Conclusion

- Formulated objective function & constraints for buzzwire OCP
- Demonstrated & evaluated trajectories on REEM-C humanoid

Discussion Question:
Buzzwire as a standard benchmark for humanoid hardware / control?

Acknowledgements

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APPENDIX

Spline collision checking (offline)

for each spline;

Solve for roots $k'(q)^T(a_3\beta^3 + a_2b^2 + a_1b + a_0) = k'(q)^T k(q)$

Check if roots occur in the valid domain of the spline

If there is exactly one valid root, then it's valid

Otherwise, it's invalid.

Obstacle viewing with Realsense