Hybrid Holistic Mobile Manipulator

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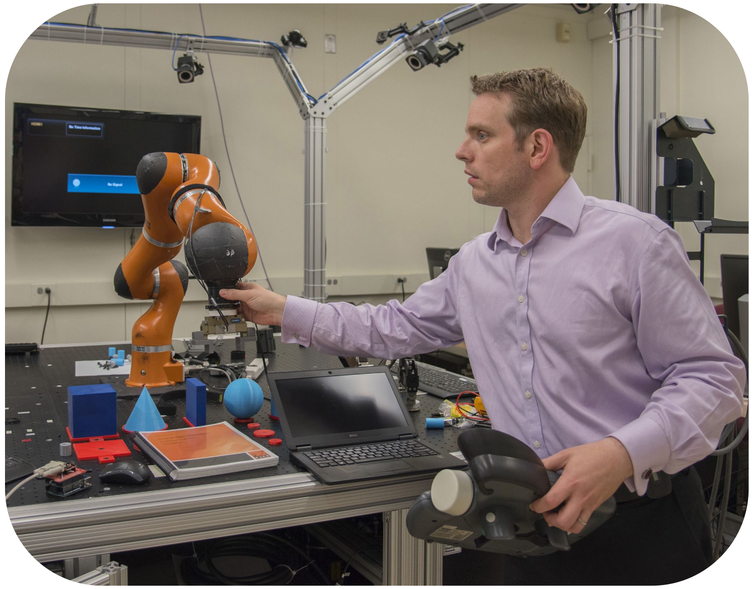
Project Overview

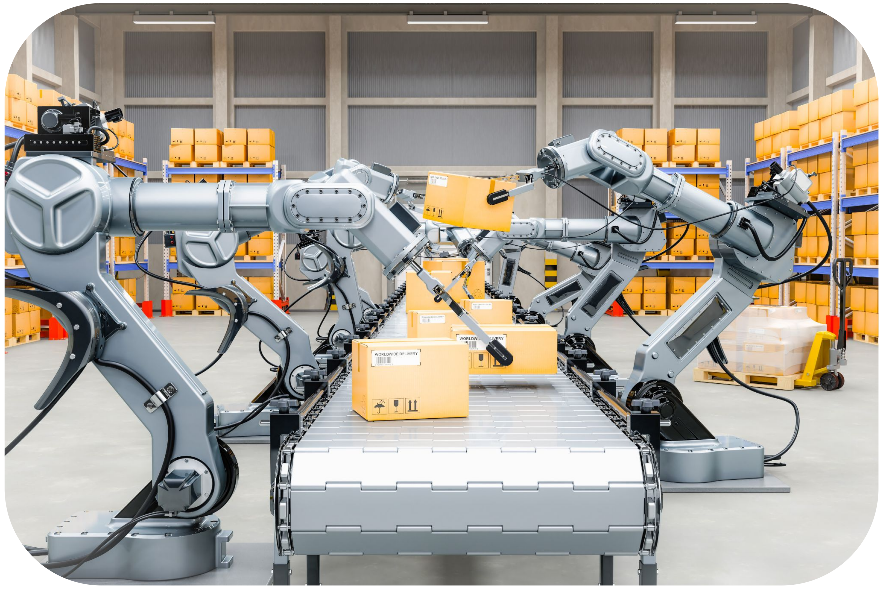
- Continuation of *Design and Implementation of a Modular Mobile Manipulator*
- Implemented a controller to govern the mobile robot in one cost function
  - Moves the system gracefully to a desired Pose
  - Maximizes Manipulability while traversing
  - Controller is reactive to changes in environment and conditions

Robotic Arms and Their Applications



Research

Service

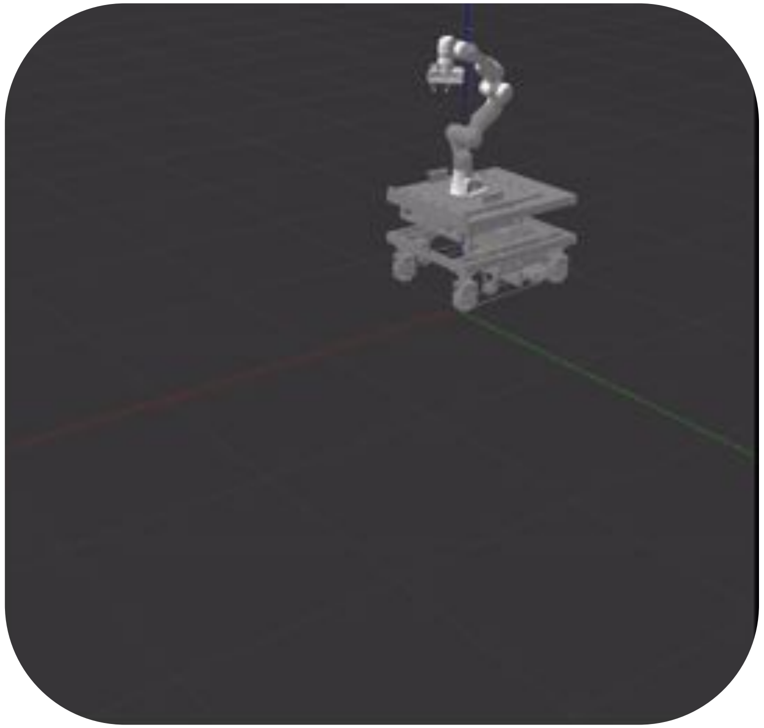


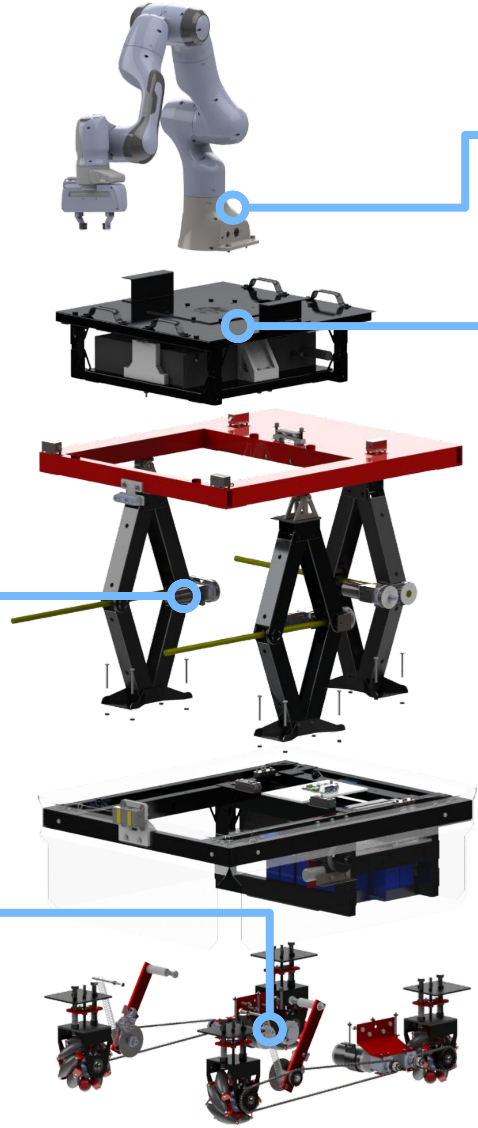
Industrial & Manufacturing

[1] https://www.nist.gov/sites/default/files/images/2016/11/15/16el014_jeremy_marvel_robotic_arm_hr.jpg
[2] https://i.ytimg.com/vi/JvS6z4xan9w/maxresdefault.jpg
[3] https://robodk.com/blog/wp-content/uploads/2019/04/program-robot-conveyor.jpg

Proposed MQP Design

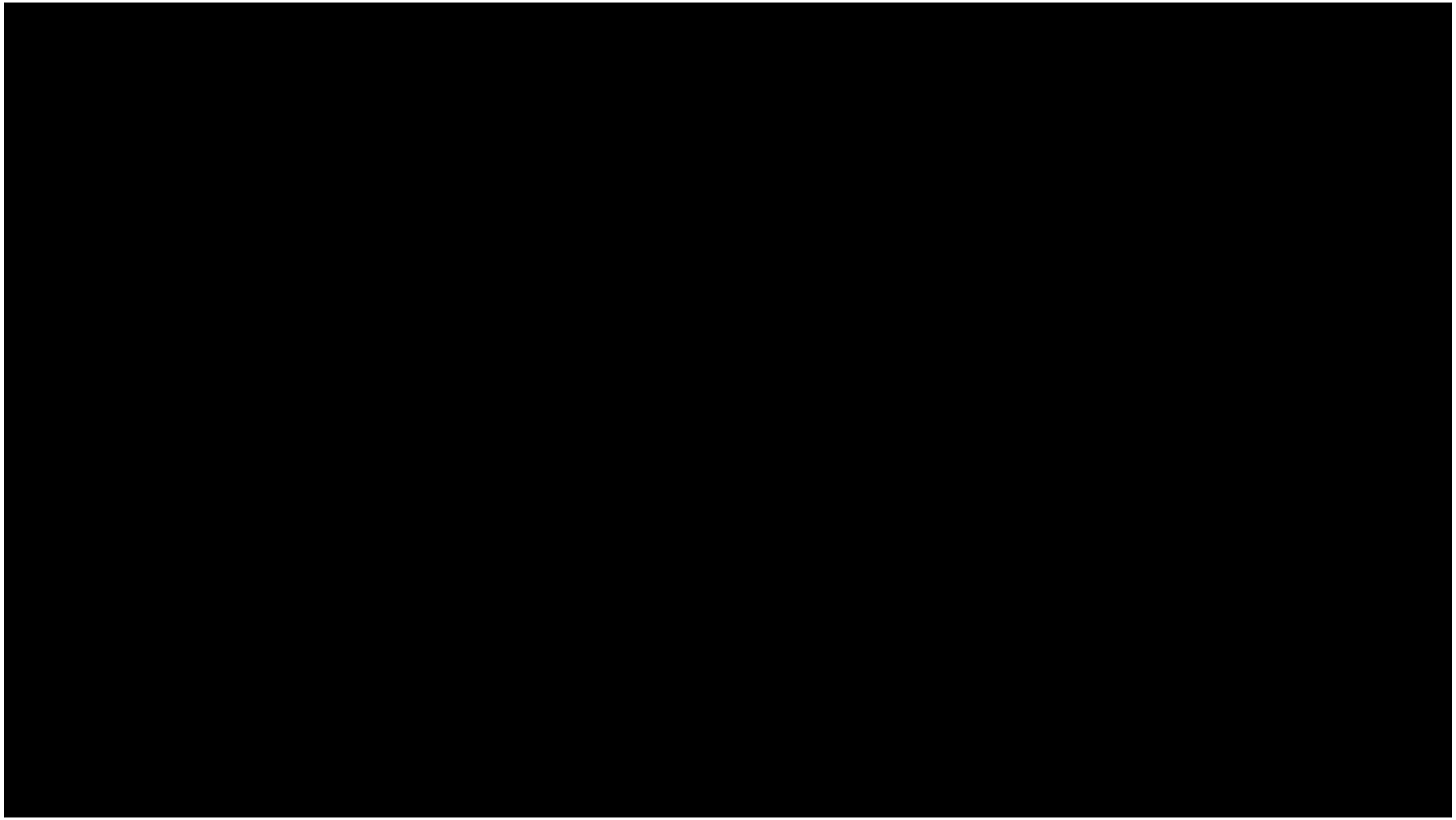
Mobility





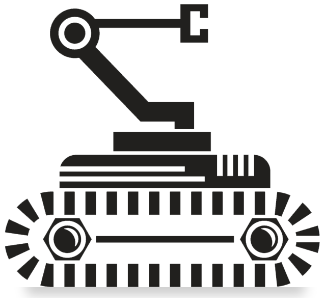
Modularity

Robot Performing a Task



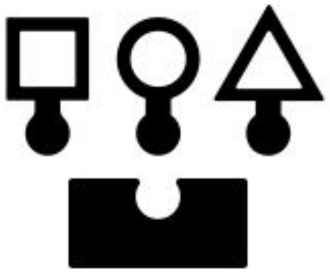
DR Objectives

Holistic



- Considers all aspects of system functionality together

Solves Joint Mismatch



- Various joint types are irrelevant

Robust & Efficient

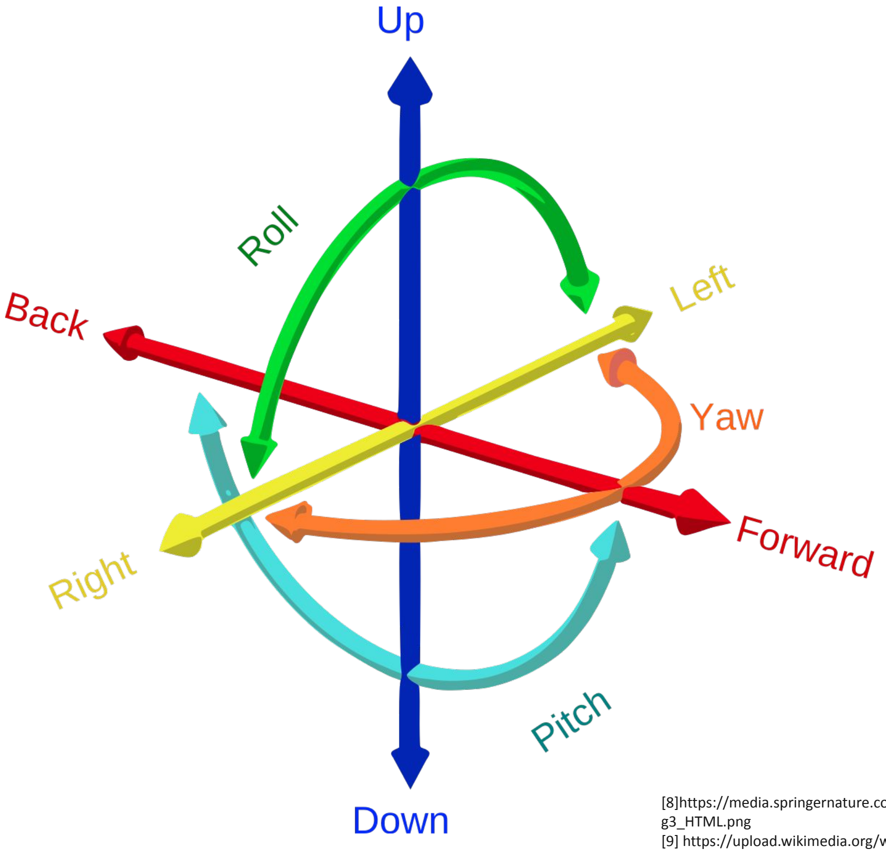
- Maximizes Manipulability during operation
- Faster solve time than existing Motion Planners

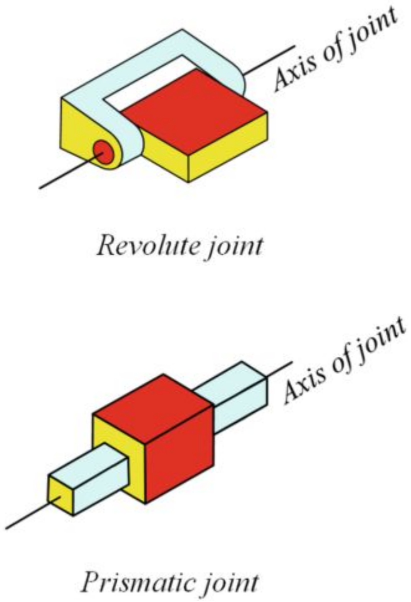
[4] https://www.veryicon.com/icons/business/business-plan-icon/project-objectives.html
[5] https://static.thenounproject.com/png/1121692-200.png
[6] https://thenounproject.com/icon/modular-858985/
[7] https://de.maplesoft.com/images2015/solutions/robotics-icon-vector.png

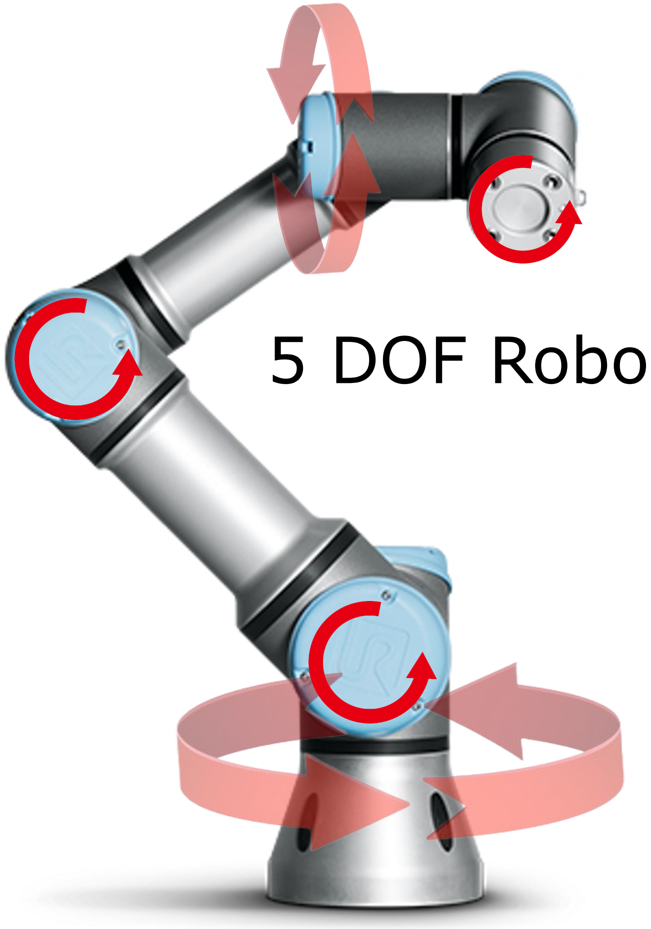
Background Terminology & Info

What is a Degree of Freedom (DOF)?

- Ability to translate or rotate about an axis
- DOF of a Robot Arm = # of joints



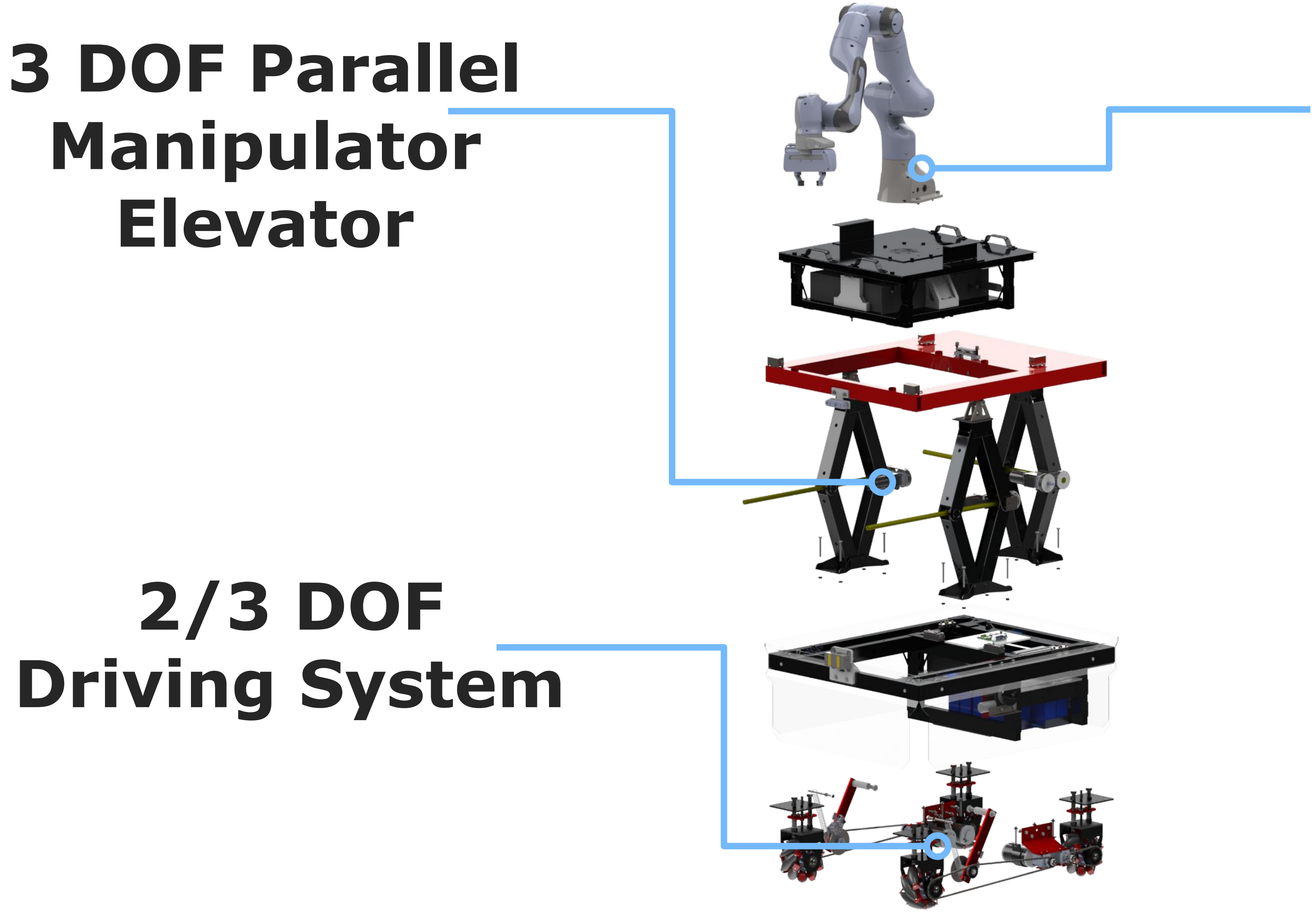




5 DOF Robot Arm

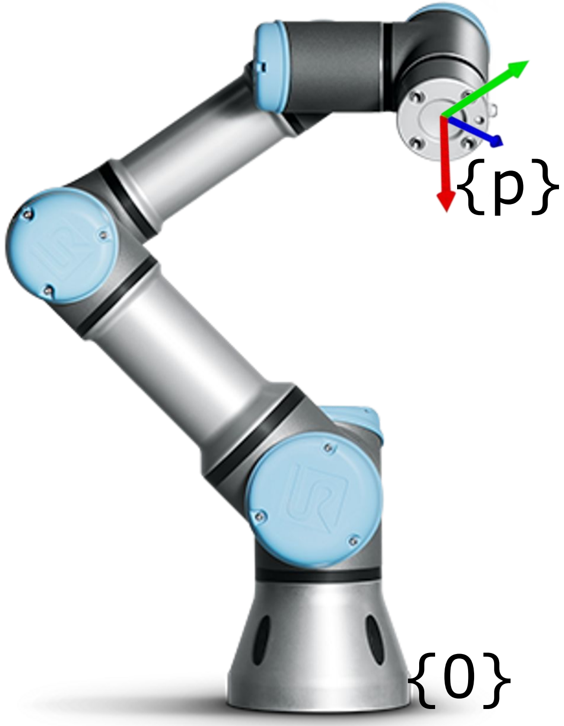
[8]https://media.springernature.com/lw685/springer-static/image/chp%3A10.1007%2F978-3-030-93220-6_1/MediaObjects/133289_3_En_1_Fig3_HTML.png
[9] https://upload.wikimedia.org/wikipedia/commons/thumb/2/2a/6DOF.svg/1200px-6DOF.svg.png
[10] https://cdn.shopify.com/s/files/1/1750/5061/products/ur5_300x300.png?v=1541621897

Integrated Redundancy



=12/13 DOF System

Robot Arm Forward Kinematics



$$p = F(q)$$

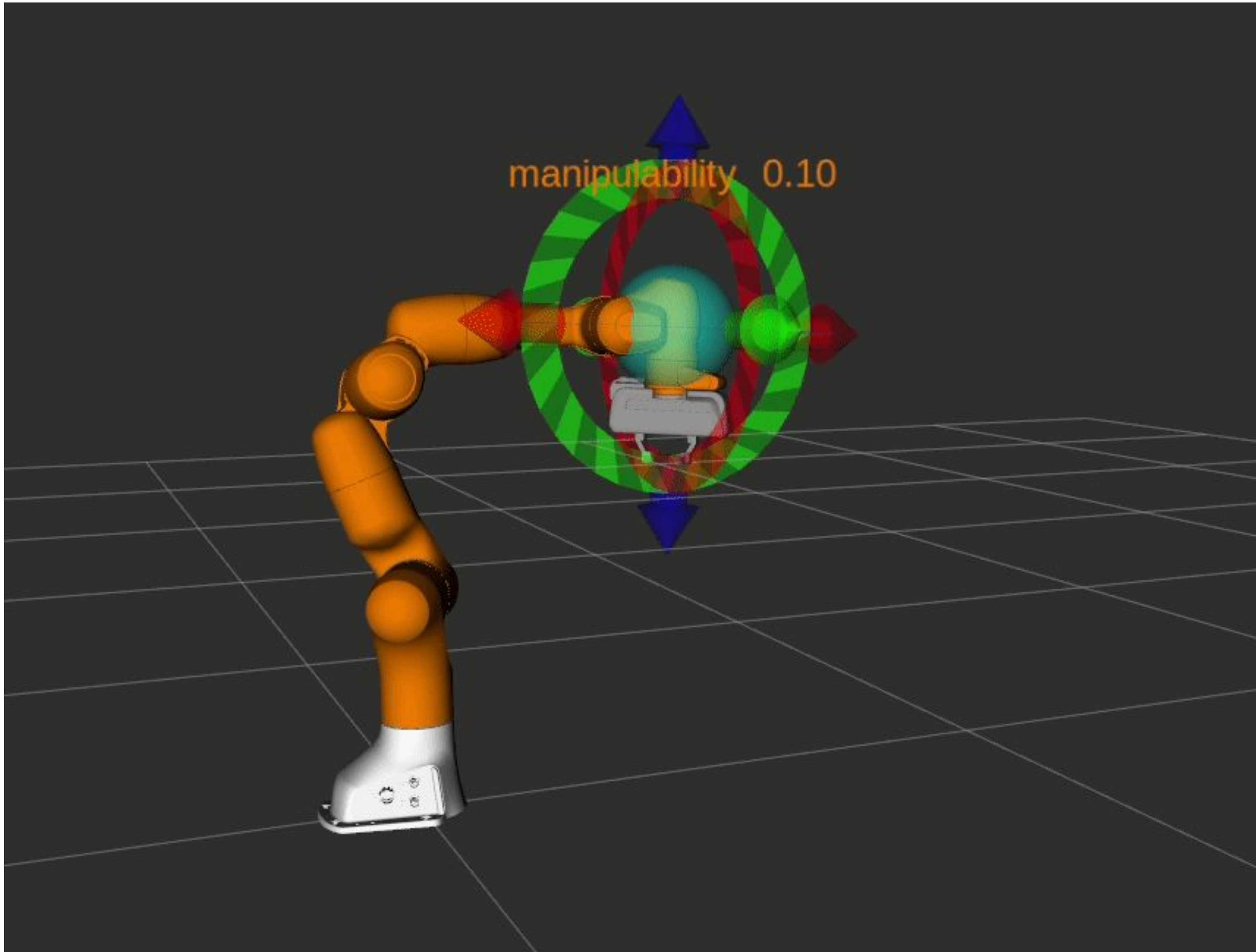
$$\frac{d}{dt}(p) = \frac{d}{dt}(F(q)) \Rightarrow \boxed{v = J(q)\dot{q}}$$

$$p = \begin{bmatrix} [x] \\ [y] \\ [z] \\ [a] \\ [b] \\ [c] \end{bmatrix}, \quad v = \begin{bmatrix} [x/s] \\ [y/s] \\ [z/s] \\ [a/s] \\ [b/s] \\ [c/s] \end{bmatrix}$$

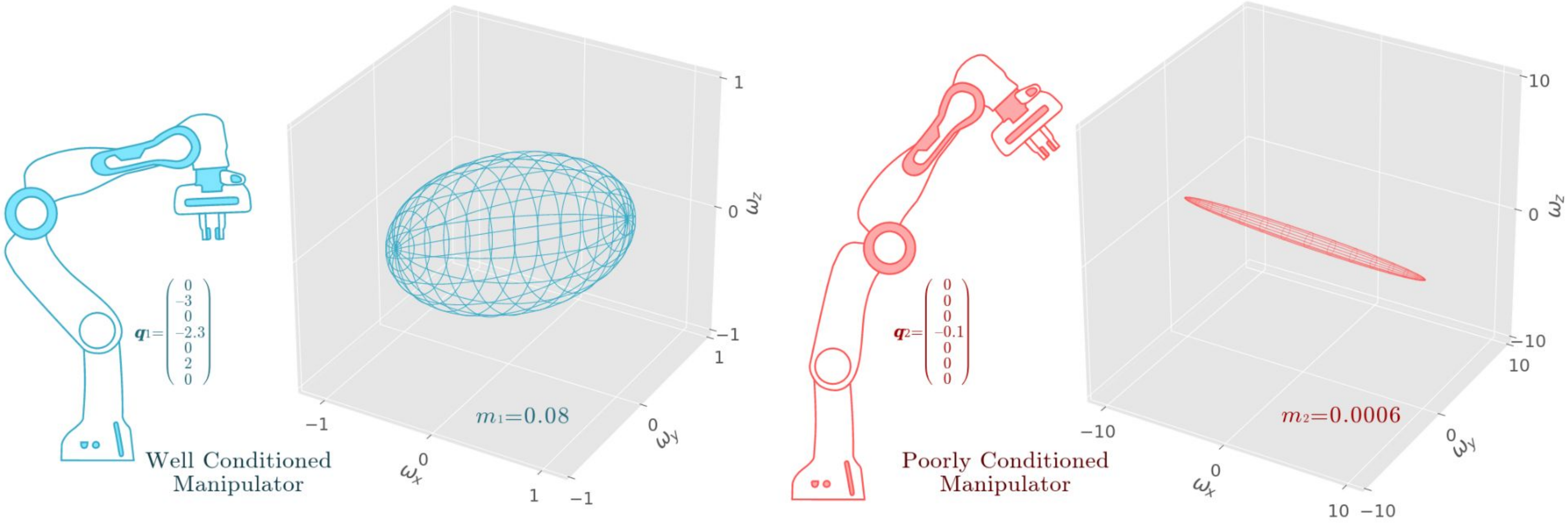
Kinematically Redundant Pose Exploration

- End Effector Pose remains *constant*

- Arm Configuration and Manipulability index can *change*



What is Manipulability?

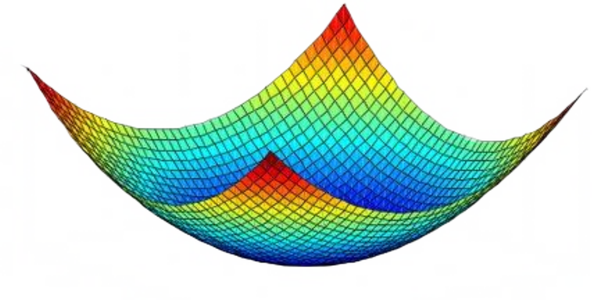


[1] https://jhavl.github.io/mmc/

Proposed Holistic Controller

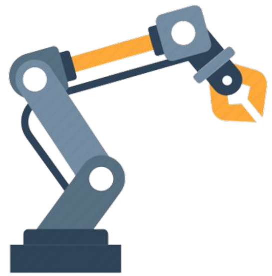
Holistic Controller Basics

Quadratic Program



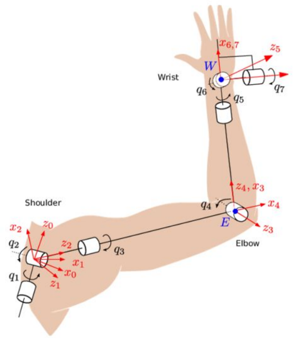
- Model system as multivariate Quadratic Program

Maximize Manipulability



- Set additional sub objectives to maximize “good” robot configurations

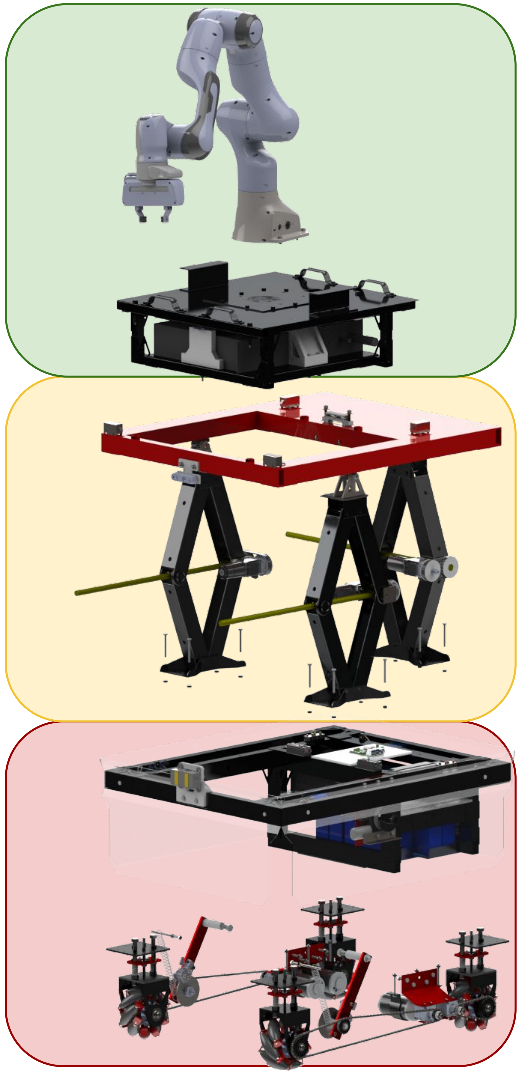
Simplify System

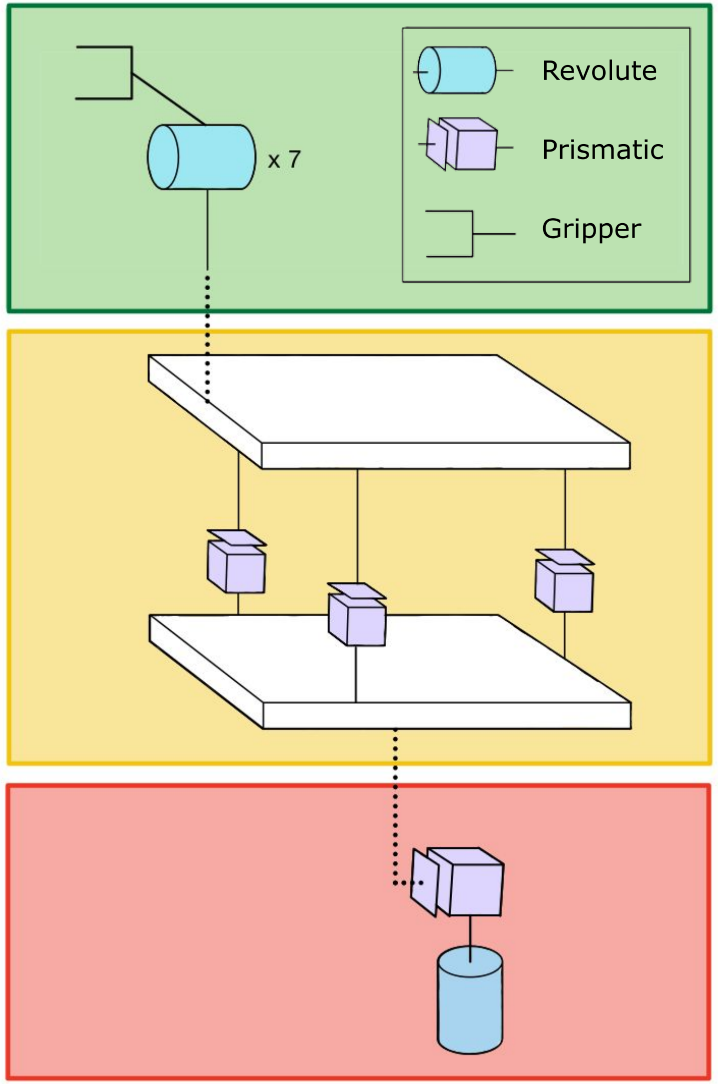


- Decompose System into Linkages and Joints

[11] https://qph.cf2.quoracdn.net/main-qimg-e682b0c1029917edb4dafa63fb6d6c2c-pjlq
[12] https://cdn-icons-png.flaticon.com/512/936/936827.png
[13]https://encrypted-tbn0.gstatic.com/images?q=tbn:ANd9GcTLXrjszmrwx-FubE6sg0eAsIkOYpesEfjeAzqtbCFsux6DXLplaNDXmRGBh8H8BRbuP5Y&usqp=CAU

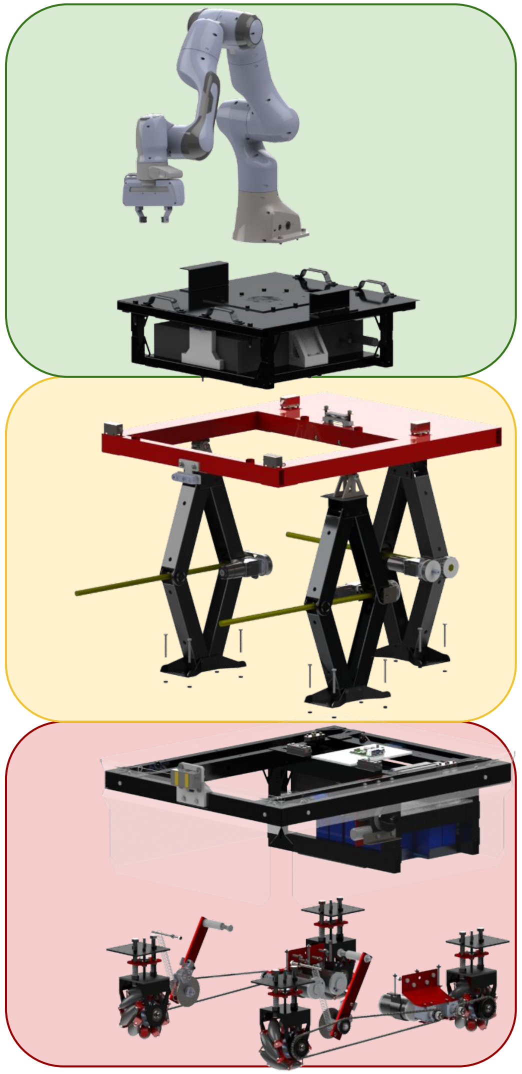
Simplifying System into Prismatic/Revolute Joints & Linkages

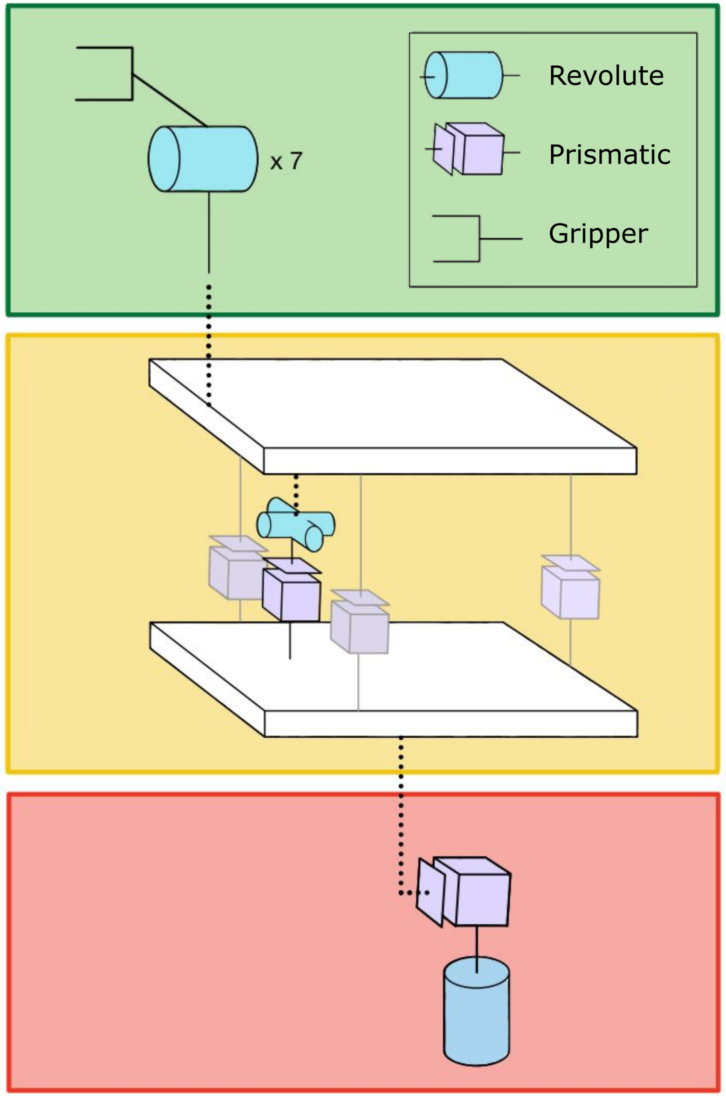




- 7 DOF *Serial* Linkage
- 3 DOF *Parallel* Linkage
- 2 DOF *Serial* Linkage

Simplify Elevator into Serial Manipulator





Pivoting

Vertical Translation

Quadratic Program Background

$$\begin{array}{ll} \text{minimize} & (1/2)x^T P x + q^T x \\ \text{subject to} & Gx \leq h \\ & Ax = b \end{array}$$

x: Optimization Variables

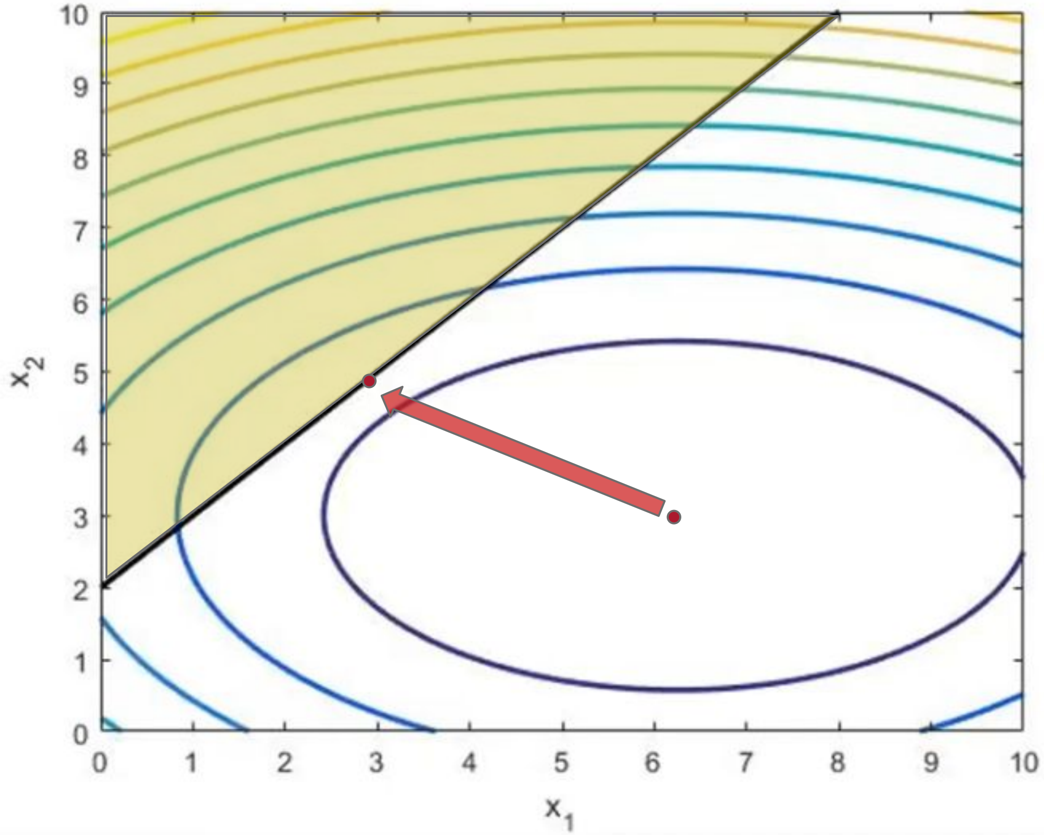
P, q: Define general QP

G, h: Inequality Constraints

A,b: Equality Constraints

Simple QP Example

$$min_{x_1,x_2} : \ cost = 0.4x_1^2 - 5x_1 + x_2^2 - 6x_2 + 50$$
$$subject\ to : \ x_2 - x_1 \geqslant 2$$



$$x_1 = 2.5$$
$$x_2 = 4.5$$
$$cost = 33.25$$

Robot Arm RRMC Controller with QP

Recall:

$$\begin{array}{ll} \text{minimize} & (1/2)x^T P x + q^T x \\ \text{subject to} & Gx \leq h \\ & Ax = b \end{array}$$

$$v_{[6x1]} = J_{[6xn]}\dot{q}_{[nx1]}$$

$$\dot{q} = J^{+}v$$

$$v \;\alpha\; e$$

$$e = p^{*} - p$$

$$min_{\dot{q}} : \; f_0(\dot{q}) = \frac{1}{2}\dot{q}^T 1_n \dot{q}$$

$$subject\ to: \; \begin{array}{l} J(q)\dot{q} = v \\ \dot{q}^{-} \leqslant \dot{q} \leqslant \dot{q}^{+} \end{array}$$

Resolved Rate Motion Controller

RRMC as QP

QP of Mobile Manipulator

$$min_{\dot{q}}: \; f_0(\dot{q}) = \frac{1}{2} x^T Q x + C^T x$$ Objective Function

$$subject\ to: \; \mathcal{J}(q)x = {}^{b}v_e$$ RRMC with Tolerance

$$Ax \leqslant B$$ Joint Position Limits

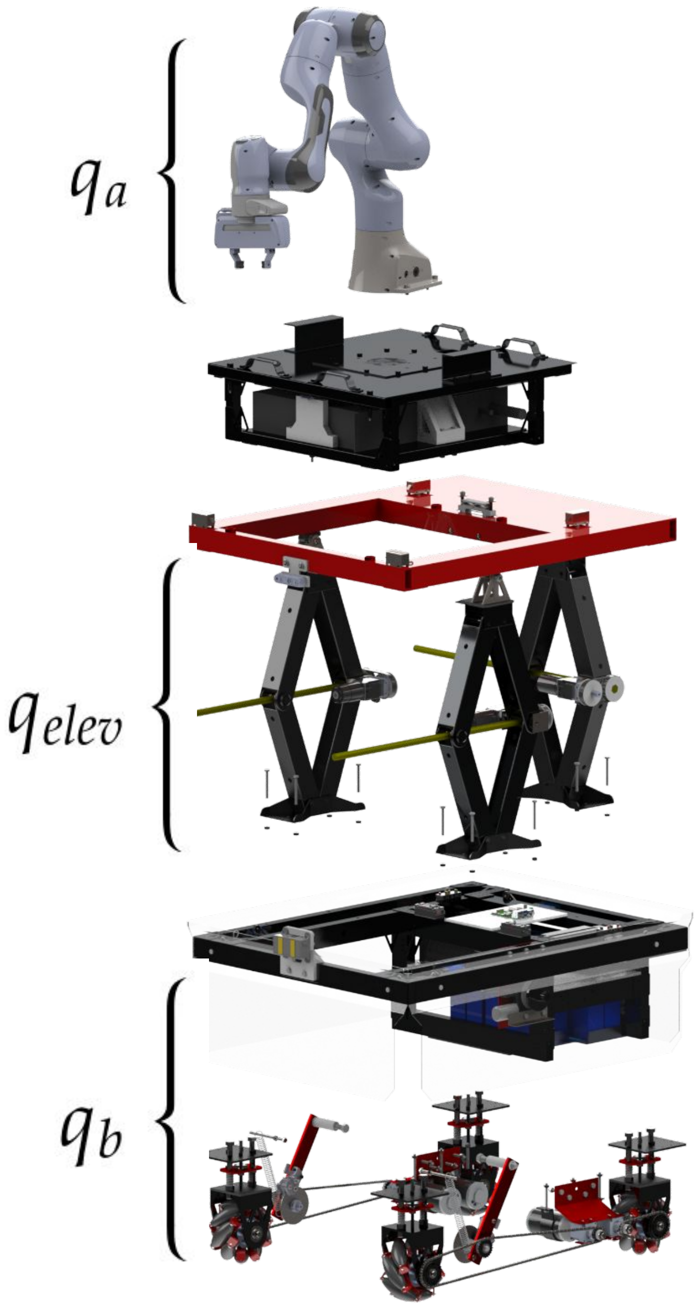
$$X^- \leqslant x \leqslant X^+$$ Joint Velocity Limits

- $x = \begin{bmatrix} \dot{q} \\ \delta \end{bmatrix}$

  $\dot{q}$: Joint Velocities

  δ: Cartesian Tolerance

- QP evaluated at every instance



Subject To Conditions

$$min_{\dot{q}} : \ f_0(\dot{q}) = \frac{1}{2} x^T \boxed{Q} x + \boxed{C^T} x$$ Objective Function

$$subject\ to : \mathcal{J}(q)x = {}^b v_e$$ RRMC with Tolerance

$$Ax \leqslant B$$ Joint Position Limits

$$X^- \leqslant x \leqslant X^+$$ Joint Velocity Limits

RRMC with Tolerance

$$\mathcal{J}(q)x = {}^b v_e$$

$$\mathcal{J}(q) = \left[\ {}^b J_e(q) \ \ 1_{6x6} \ \right]$$

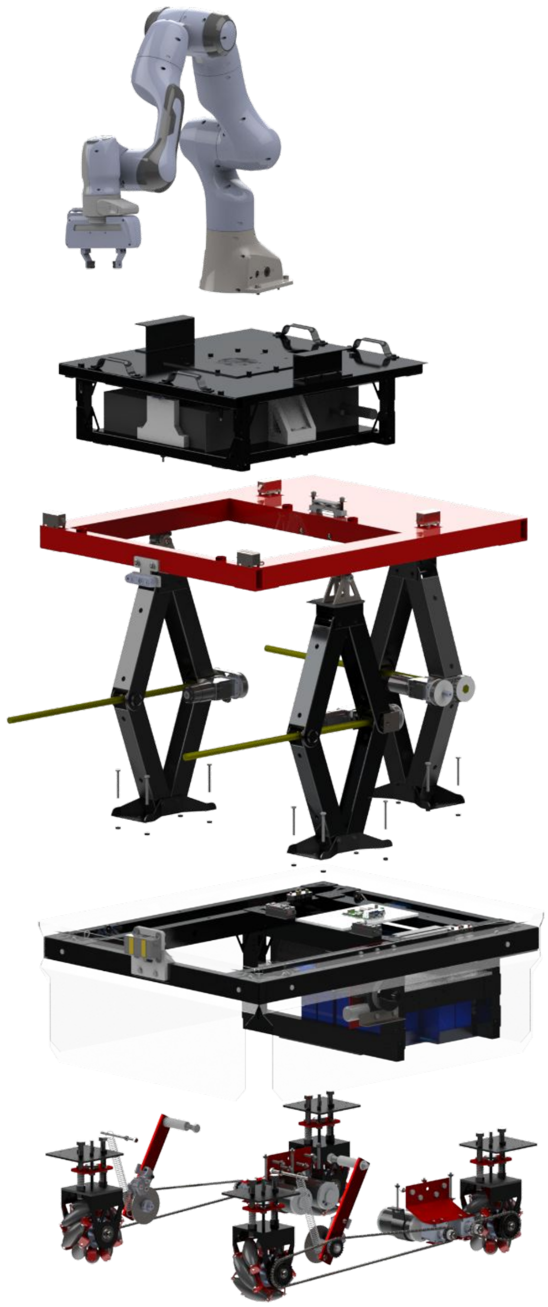
$${}^b v_e(t) = {}^b v_e^*(t) - \delta(t)$$

Joint Velocity Limits

$$X^- \leqslant x \leqslant X^+$$

$$X^- = \begin{bmatrix} \dot{q}^- \\ \delta^- \end{bmatrix}, \ X^+ = \begin{bmatrix} \dot{q}^+ \\ \delta^+ \end{bmatrix}$$

$$x = \begin{bmatrix} \dot{q} \\ \delta \end{bmatrix}$$



Subject To Conditions

$$min_{\dot{q}} : \ f_0(\dot{q}) = \frac{1}{2} x^T Q x + C^T x$$ Objective Function

$$subject\ to : \mathcal{J}(q)x = {}^b v_e$$ RRMC with Tolerance

$$Ax \leqslant B$$ Joint Position Limits

$$X^- \leqslant x \leqslant X^+$$ Joint Velocity Limits

Joint Position Limits

$$Ax \leqslant B$$

$$A = \begin{bmatrix} A_b \\ A_{elev_p} \\ A_{elev_r} \\ A_a \\ 1_6 \end{bmatrix} = [\pm 1_{nxn+6}] \qquad B = \begin{bmatrix} 0_b \\ B_{elev_p} \\ B_{elev_r} \\ B_a \end{bmatrix}$$

$$B_{elev_{p,r}}, B_a = \begin{bmatrix} \dfrac{q_{elev_{p,r,a}} - p_{s_{elev_{p,r,a}}}}{p_{i_{elev_{p,r,a}}} - p_{s_{elev_{p,r,a}}}} \\ \vdots \\ \dfrac{q_n - p_{s_{elev_{p,r,a}}}}{p_{i_{elev_{p,r,a}}} - p_{s_{elev_{p,r,a}}}} \end{bmatrix}$$

Objective Function Analysis: Q

$$min_{\dot{q}} : \; f_0(\dot{q}) = \frac{1}{2} x^T \boxed{Q} x + \boxed{C^T} x$$ Objective Function

$$subject\ to: \mathcal{J}(q)x = {}^b v_e$$ RRMC with Tolerance

$$Ax \leqslant B$$ Joint Position Limits

$$X^- \leqslant x \leqslant X^+$$ Joint Velocity Limits

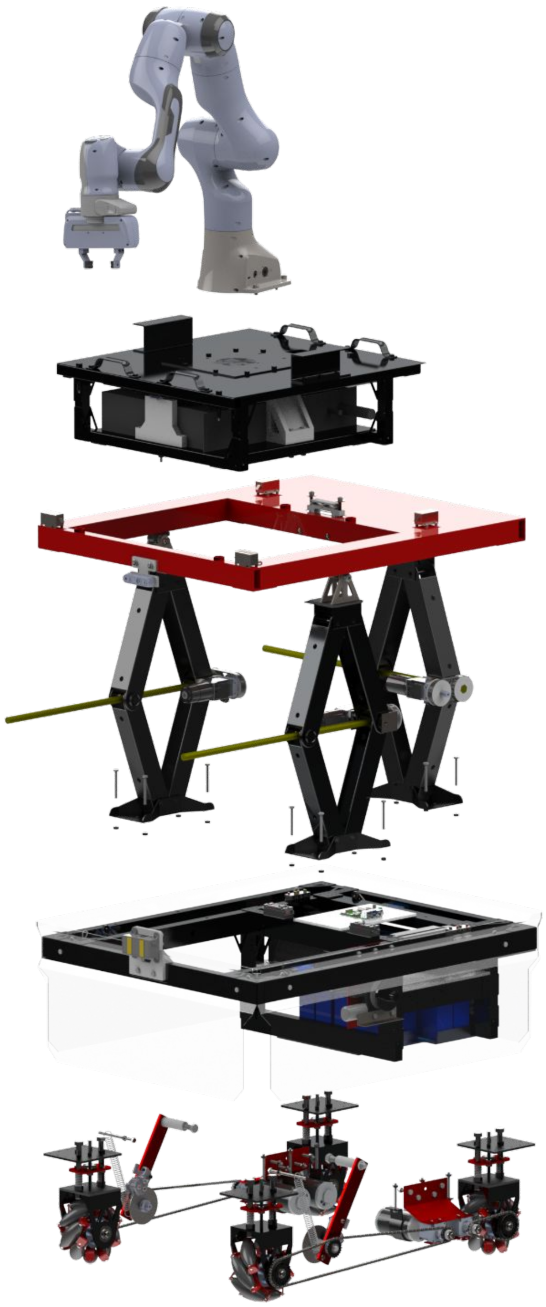
Objective Function: Q

$$k_a = constant$$

$$Q = \begin{bmatrix} diag(\lambda_b) & & & 0_{(n+6)x(n+6)} \\ & diag(\lambda_{elev}) & & \\ & & diag(k_a) & \\ 0_{(n+6)x(n+6)} & & & diag(\lambda_\delta) \end{bmatrix}$$

$$\lambda_{elev} = \left(\frac{1}{||e||}, \; k_{elev_r} \right)$$

$$\lambda_b, \lambda_\delta = \frac{1}{||e||}$$



Objective Function Analysis: C^T

$$min_{\dot{q}} : \ f_0(\dot{q}) = \frac{1}{2} x^T \boxed{Q} x + \boxed{C^T} x$$

Objective Function

$$subject\ to: \mathcal{J}(q) x = {}^{b}v_e$$

RRMC with Tolerance

$$Ax \leqslant B$$

Joint Position Limits

$$X^- \leqslant x \leqslant X^+$$

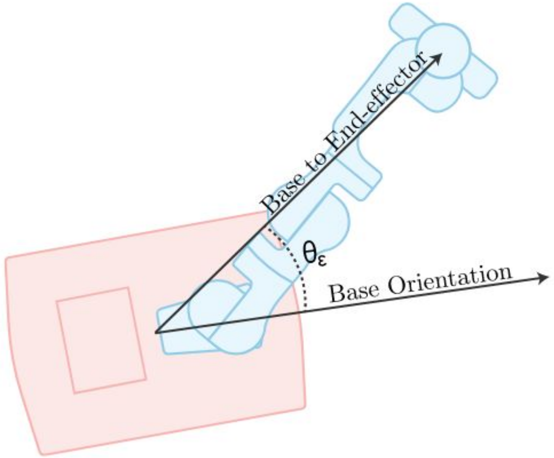
Joint Velocity Limits

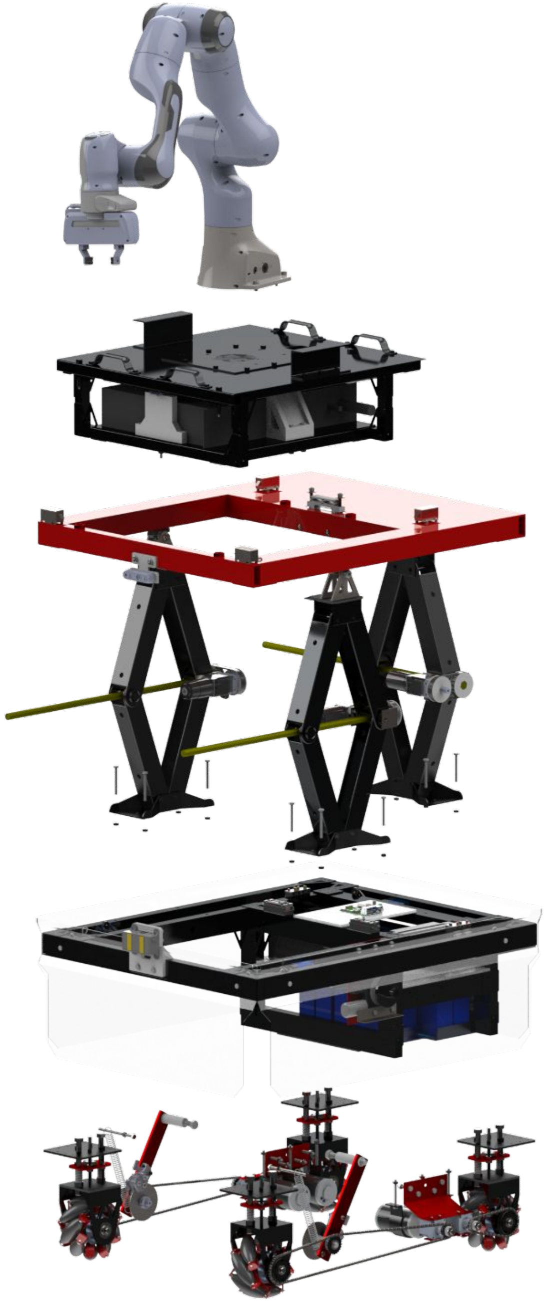
Objective Function: C^T

$$J_m = \begin{bmatrix} 0_b \\ J_{m,a}^T \end{bmatrix}$$

$$C = \begin{bmatrix} J_m + \epsilon \\ 0_{6x1} \end{bmatrix}$$

$$\epsilon = \begin{bmatrix} -k_\epsilon \theta_\epsilon \\ 0_{n-1} \end{bmatrix}$$





The Manipulability Jacobian J_m^T

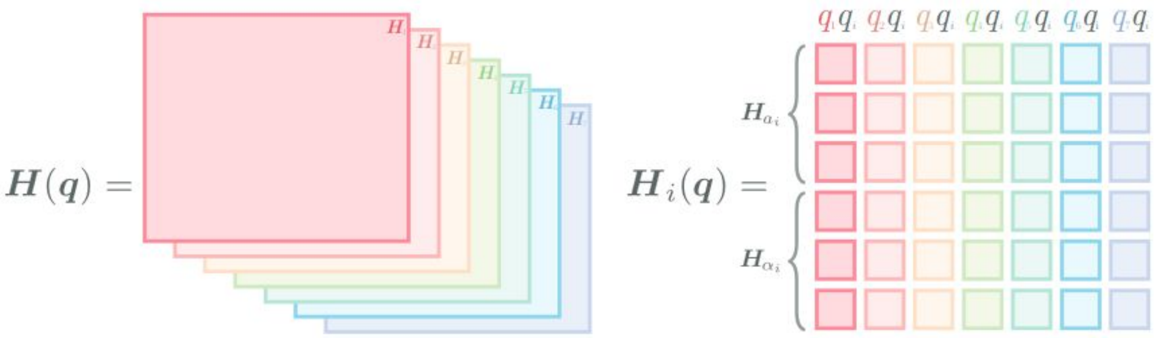
$$m(q) = \sqrt{det\left(\hat{J}(q)\hat{J}(q)^{\mathrm{T}}\right)}$$

$$\dot{m} = J_m^T(q)\dot{q} \quad \longleftrightarrow \quad v = J(q)\dot{q}$$

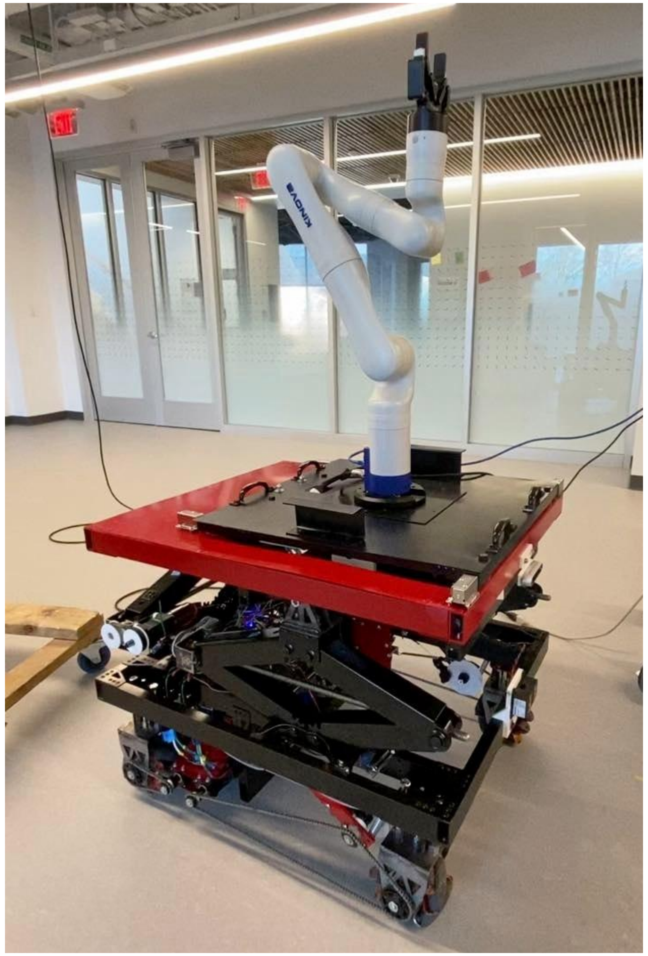
$$J_{m,a}^T = m\begin{bmatrix} vec\left(J(q)H_1(q)^T\right)^T vec\left(J(q)J(q)^T\right)^{-1} \\ vec\left(J(q)H_2(q)^T\right)^T vec\left(J(q)J(q)^T\right)^{-1} \\ \vdots \\ vec\left(J(q)H_n(q)^T\right)^T vec\left(J(q)J(q)^T\right)^{-1} \end{bmatrix}$$

Hessian Tensor Review

$$\begin{aligned}
\dot{\mathbf{J}} &= \frac{\mathrm{d}\mathbf{J}(\boldsymbol{q})}{\mathrm{d}t} \\
&= \frac{\partial \mathbf{J}(\boldsymbol{q})}{\partial q_1}\dot{q}_1 + \frac{\partial \mathbf{J}(\boldsymbol{q})}{\partial q_2}\dot{q}_2 + \cdots + \frac{\partial \mathbf{J}}{\partial q_n}\dot{q}_n \\
&= \begin{pmatrix} \frac{\partial \mathbf{J}(\boldsymbol{q})}{\partial q_1} & \frac{\partial \mathbf{J}(\boldsymbol{q})}{\partial q_2} & \cdots & \frac{\partial \mathbf{J}(\boldsymbol{q})}{\partial q_n} \end{pmatrix}\dot{\boldsymbol{q}} \\
&= \mathbf{H}(\boldsymbol{q})\dot{\boldsymbol{q}} \\
&= \begin{pmatrix} \mathbf{H}_a(\boldsymbol{q}) \\ \mathbf{H}_\alpha(\boldsymbol{q}) \end{pmatrix}\dot{\boldsymbol{q}}
\end{aligned}$$

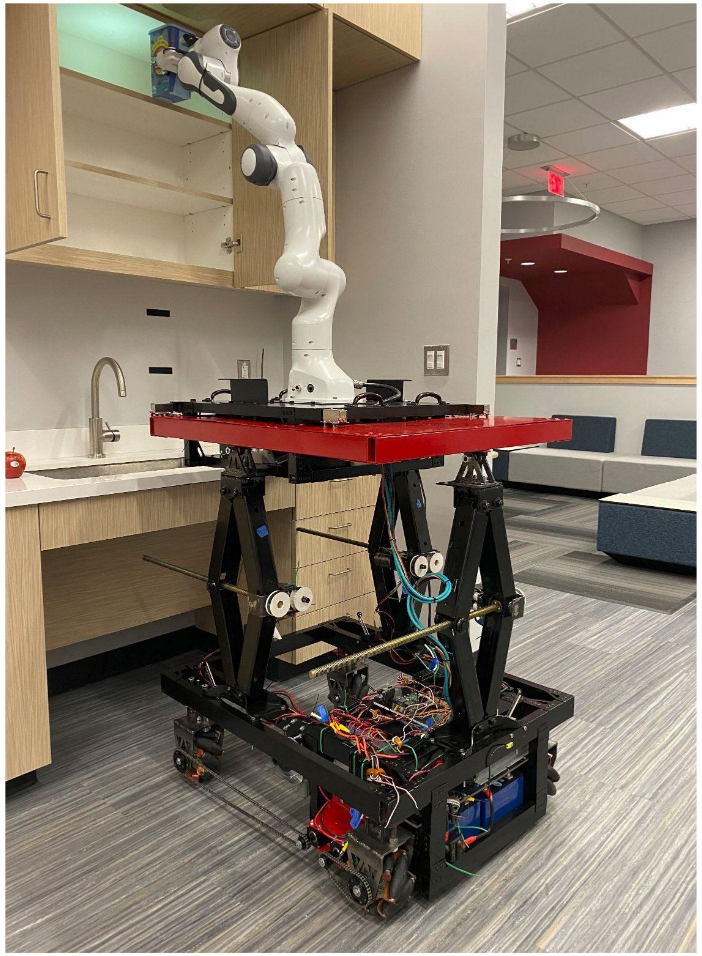


Final Robot Pictures



Modular Arm Swap

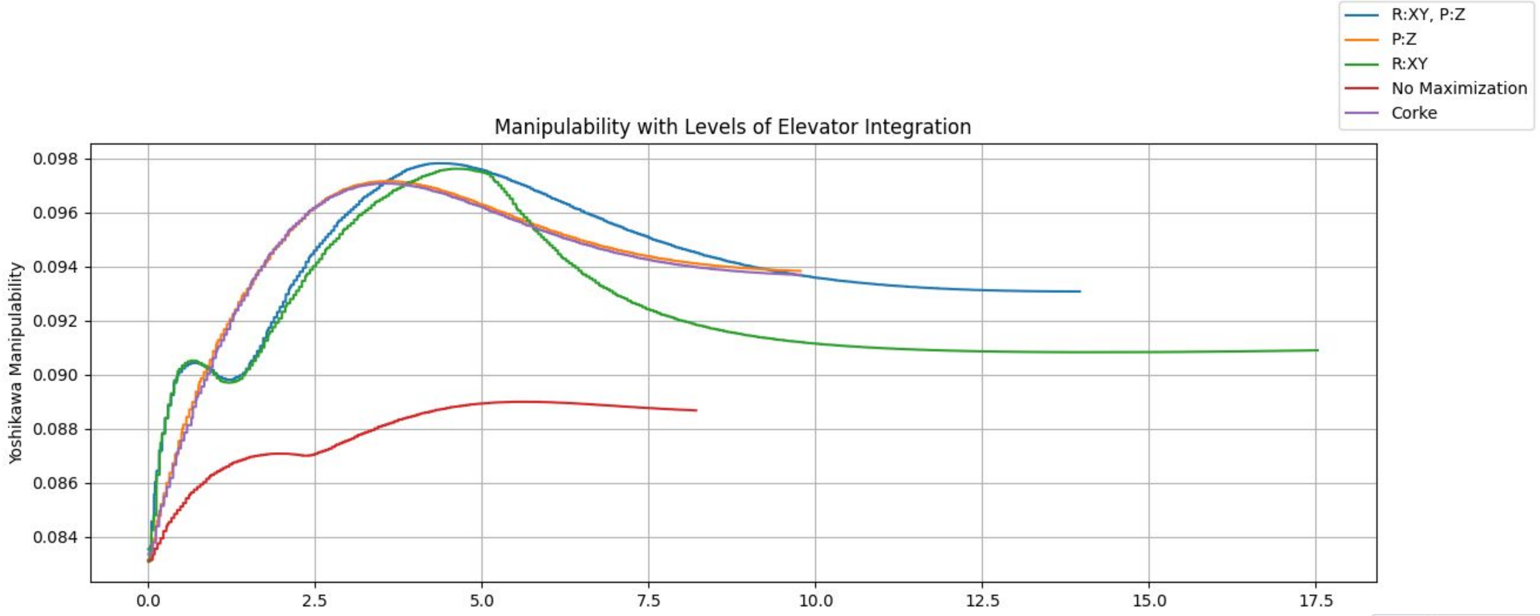
Reaching Low

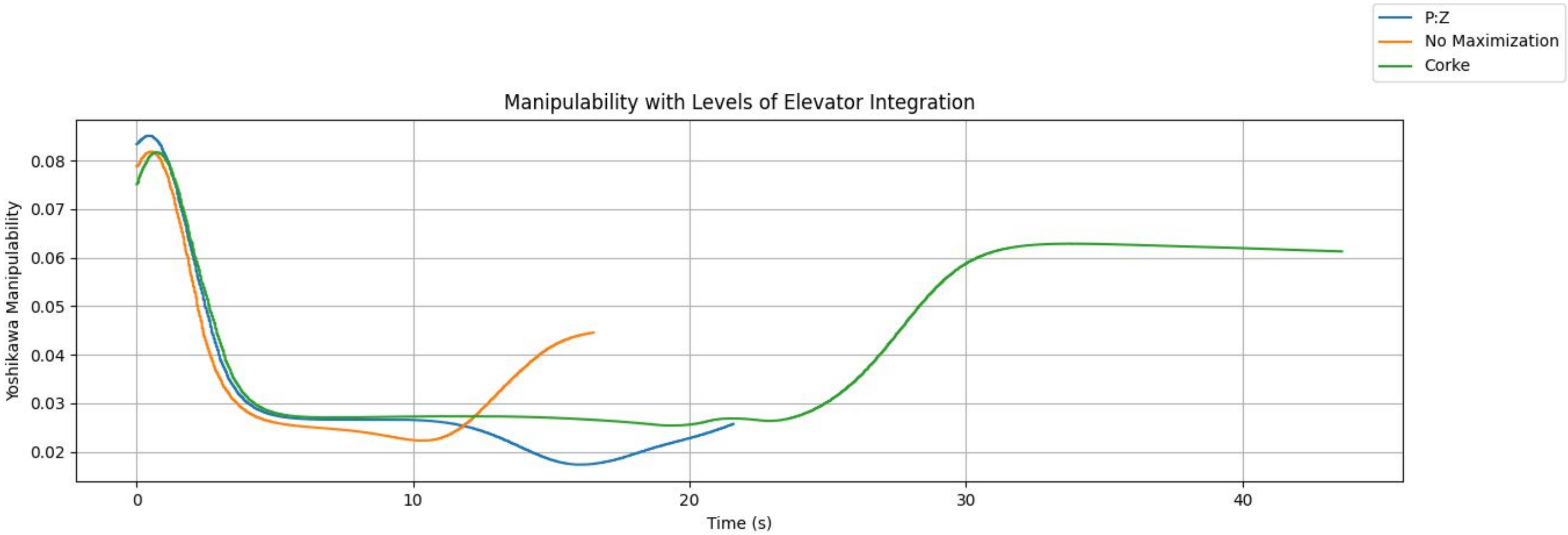


Reaching High

Video Demonstrations

Different Manipulability Approaches





Ongoing Research

1. Manipulability Weighting / Prioritizing
2. Power Manipulability Representation
3. Visualizing QP "Pitfalls"

WPI

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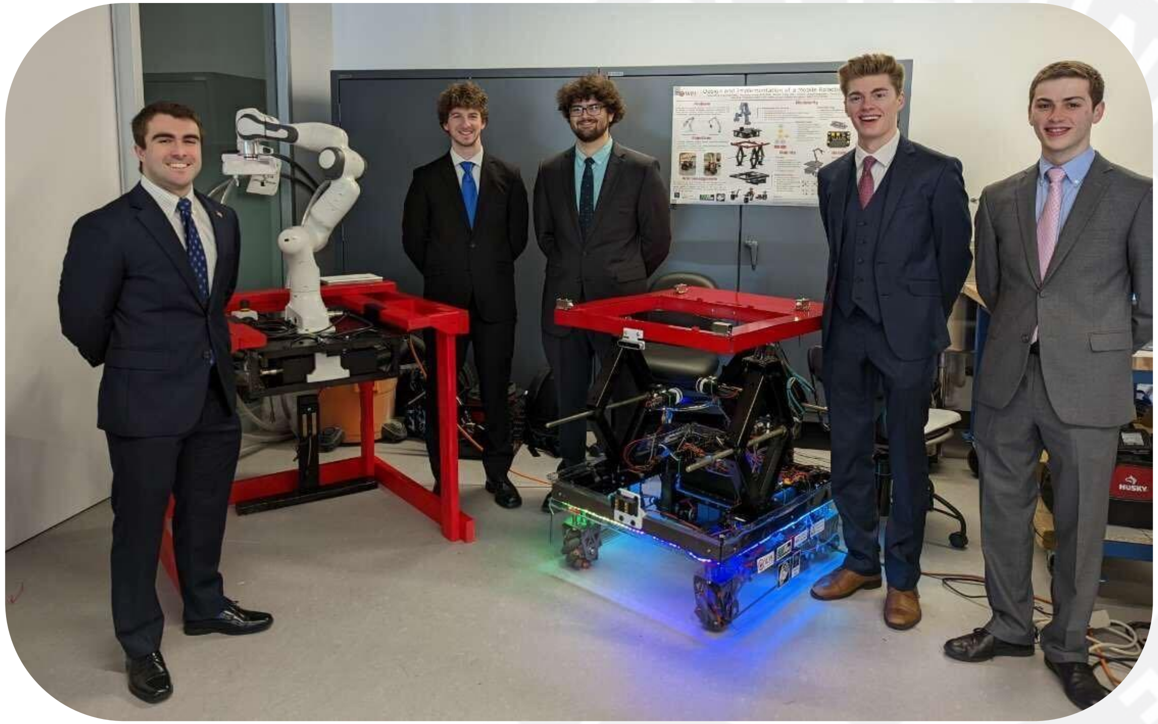
METAL RECYCLING REIMAGINED

Manipulation and Environmental Robotics lab.

Thank you for listening!

Questions?



- A project overview/problem definition
- System-level diagrams, as needed, to explain how your system operates and how it solves the problem
- More detailed design slides for key sub-systems
- Demonstrations (videos, data analysis, etc.) of system performance