National Robotics Initiative PI Meeting
October 29-30, 2018

DoE 1637969: Extra Robotic Limbs for Body Support in Kneeling and Crouching Works

H. Harry Asada, PI

Daniel J. Gonzalez, Research Assistant

Department of Mechanical Engineering

Massachusetts Institute of Technology


[redacted]

NSF
U.S. DEPARTMENT OF ENERGY
d'Arbeloff Laboratory
MITMECHE
Massachusetts Institute of Technology

Motivation:
Nuclear Waste Site Inspection

- Average worker **>50 years old**
- **Hazmat Suit** & Life-Support Equipment are **HEAVY (30lbs+)**
- **Heat Fatigue** limits work time

Can they carry cooling system & more air without feeling it?

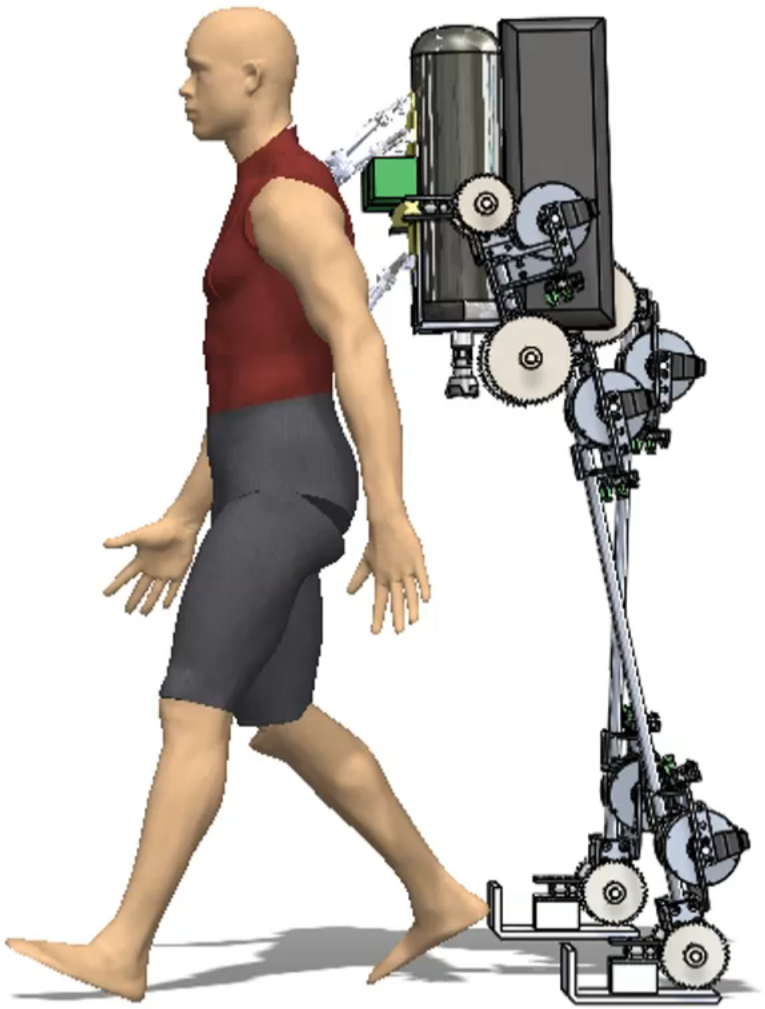
Beyond the Nuclear Waste Sites

Heavy Industry

Construction

Agriculture

Design Concept: **Extra Robotic Legs (XRL) System**



XRL can

- Carry the heavy life support equipment;
- Bear the equipment load and the human worker’s body weight;
- Brace the body, so that the worker can use both hands for a task: Hands free;
- Support transitioning between standing and crouching postures.

XRL differs from Exoskeletons.

Human-XRL System

4 legs and 2 arms: Half human and half robot

Challenges:

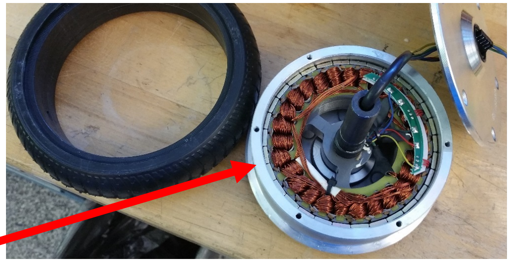
- Actuators and power;
- Multi-posture body support and transition support;
- Gait synchronization with the human legs;
- Fail-safe design; and
- Human-robot communication

https://i.ebayimg.com/images/i/352241492514-0-1/s-l1000.jpg

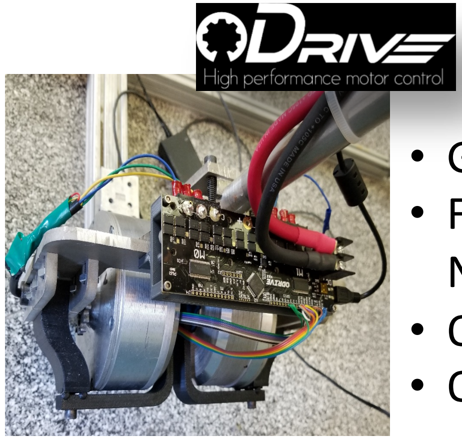
Centaur

Design

Hoverboard Wheel Motor



Blushless DC motor
Torque Const. = 0.45 Nm/A
Max. Torque = 23 Nm
Cost: $20 each
Gear ratio 1:8 (Backdrivable)

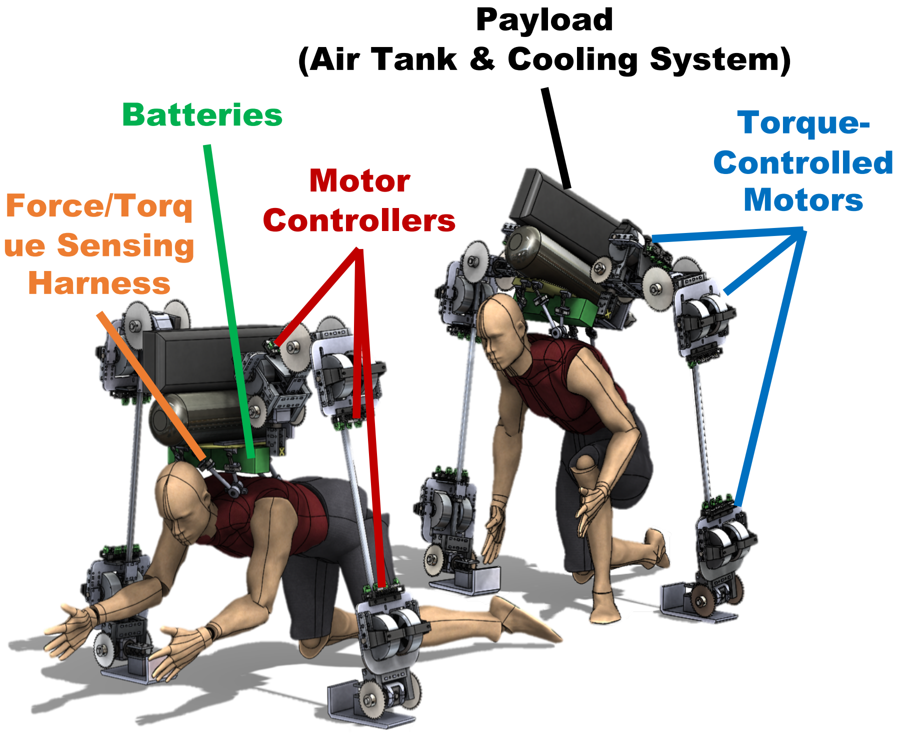


- GaNTFET drivers :
- Fast switching (< 25 ns)
  NO HEAT SINK
- Open source software;
- Only $60 per axis


[redacted]

6 DOF for each XRL: total 12 DOF

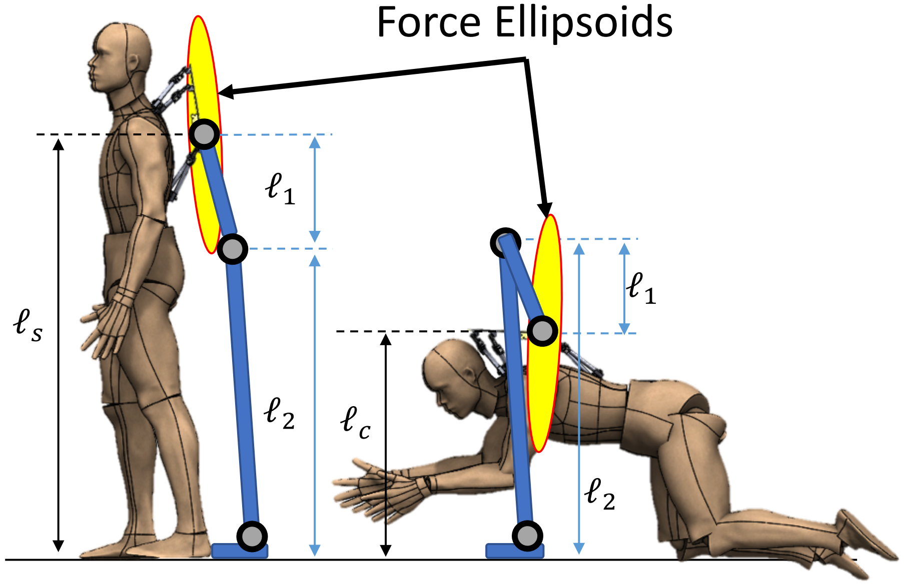
Squat/stand up with 180 lbs (~82kg)
total robot + payload + assistive force



Reducing Torque Requirements

1. Exploit Dual Singularity

At both standing and crawling postures, the XRL is near singular configurations. Only small actuator torque is required for bearing the load.



$$\ell_s = \ell_1 + \ell_2$$
$$\ell_c = \ell_2 - \ell_1$$

2. Null-Space Control

Exploit the null space associated with the closed kinematic chain formed by the two XRL legs. The internal force in the null space does not change the balance of forces, yet changes the distribution of joint torques. We can find an optimal distribution so that the overall joint torques at the 12 joints may be minimized.

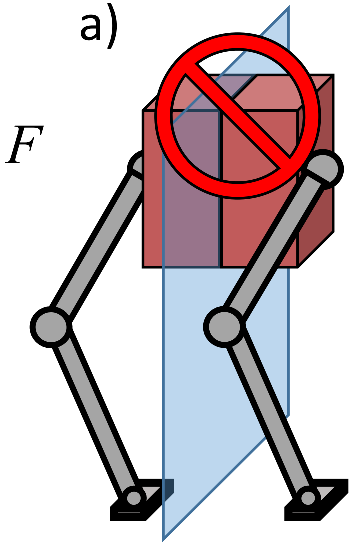
$$\tau^o(\theta) = \arg\min_{\tau} \left|\tau(\theta)\right|^2$$

Subject to $\tau = J^T(\theta)\, F$

where $J(\theta) \in \Re^{6\times 12}$

The above result depends on the configuration of the legs. The optimal configuration where the squared torque is minimum is the one where both legs are involved within the frontal plane.

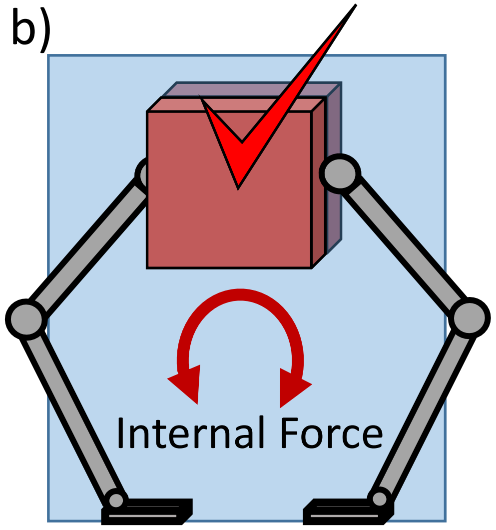
a)



Both legs are parallel to the Sagittal Plane

Max. 154 Nm

b)

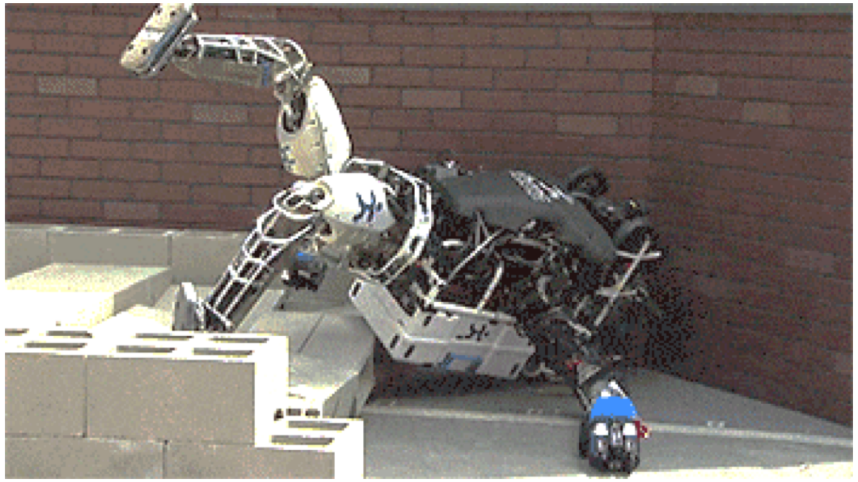


Both legs are within the Frontal Plane

→ Max. 86 Nm

Fail-safe control system architecture

Failures in the DARPA Robotics Challenge

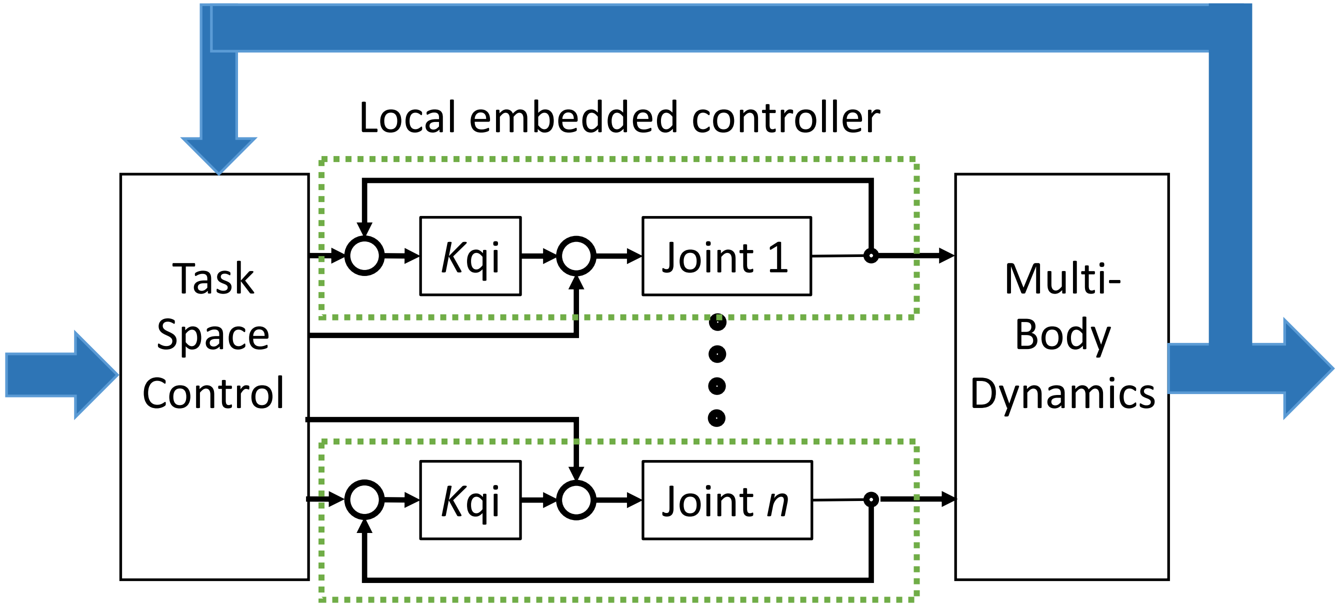


Cable connectors and communication channels are most vulnerable.

Safety is most important for wearable robots.

Fail-safe control system architecture:

In case of failures at cable connectors and communication channels, the embedded joint controllers can guarantee stable control.



Consider a special case:

Task space stiffness control of non-singular, non-redundant system

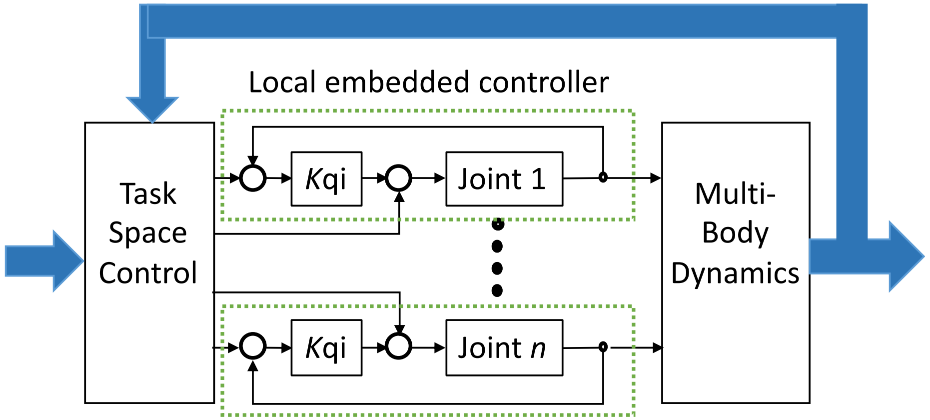
$$\begin{pmatrix} F_x \\ F_y \\ \vdots \\ N_z \end{pmatrix} = \underbrace{\begin{pmatrix} K_x & K_{xy} & \cdots & K_{x\psi} \\ K_{yx} & K_y & & K_{y\psi} \\ \vdots & & \ddots & \vdots \\ K_{\psi x} & K_{\psi y} & \cdots & K_{\psi} \end{pmatrix}}_{K_{task}} \begin{pmatrix} \Delta x \\ \Delta y \\ \vdots \\ \Delta \psi \end{pmatrix}$$

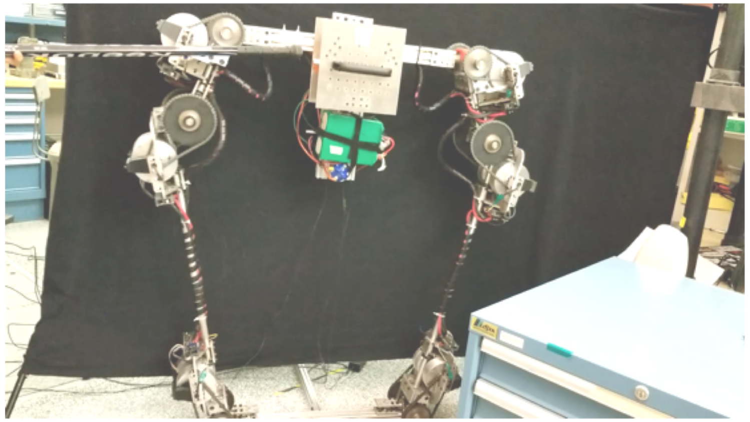
Task space stiffness

$$\Delta F = K_{task} \Delta x$$

Joint space stiffness

$$\Delta \tau = K_{joint} \Delta \theta$$





Divide the joint feedback gain matrix into a diagonal matrix and the rest of the part.

$$K_{joint} = D_{joint} + \hat{K}_{joint}$$

$$\begin{pmatrix} k_{11} & \cdots & k_{1n} \\ \vdots & \ddots & \vdots \\ k_{n1} & \cdots & k_{nn} \end{pmatrix} = \begin{pmatrix} d_1 & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & d_n \end{pmatrix} + \begin{pmatrix} k_{11} - d_1 & \cdots & k_{1n} \\ \vdots & \ddots & \vdots \\ k_{n1} & \cdots & k_{nn} - d_n \end{pmatrix}$$

If K_{joint} Is symmetry and positive-definite, its diagonal matrix $\bar{D}_{joint}$ is positive-definite. Therefore, $\bar{D}_{joint}$ can be used for the independent joint feedback gains that make the system stable although the multivariate feedback part $\hat{K}_{joint}$ is disconnected.

The joint space stiffness, i.e. joint feedback gain matrix, is related to the task space stiffness as:

$$K_{task} = \tilde{J}^T K_{jint} \tilde{J} - \sum_i H_i \bar{\tau}_i$$

where $\tilde{J} = \dfrac{d\theta}{dp}, \quad H_i = \left\{ \dfrac{d^2\theta_i}{dp_j dp_k} \right\}$; Hessians

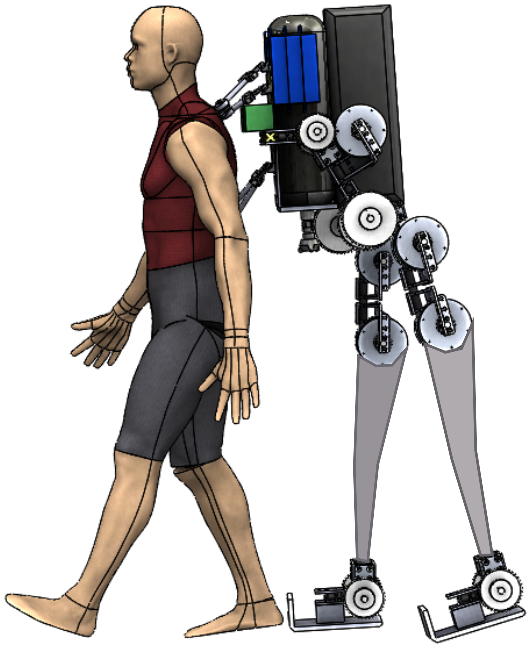
Note that, although K_{task} Is positive definite, K_{joint} is not necessarily positive definite.

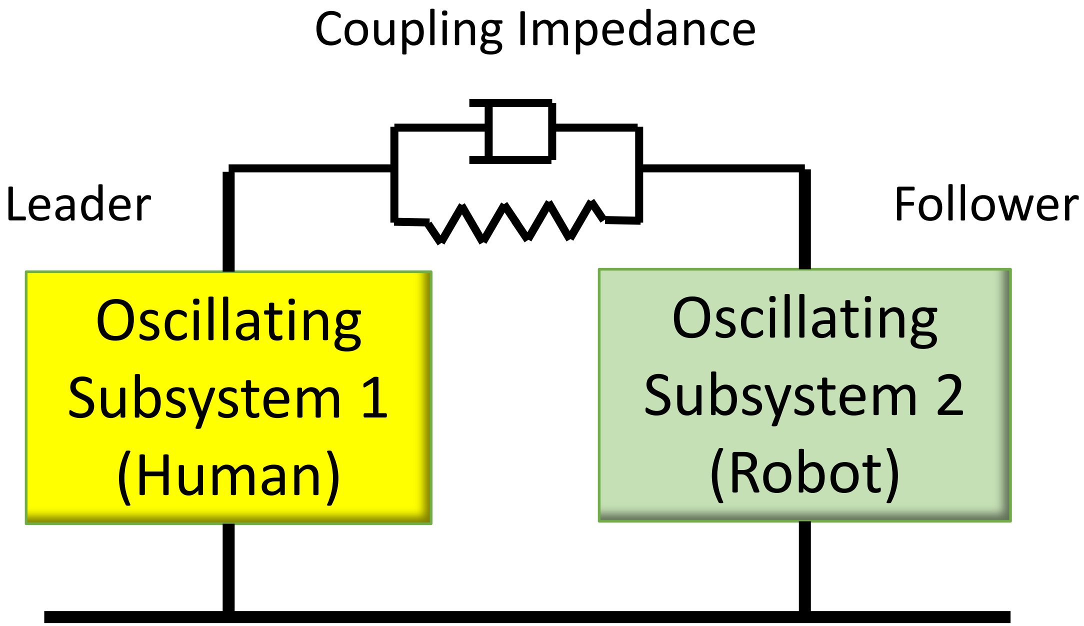
A special case where $J = \left\{ \dfrac{dp}{d\theta} \right\} \in \Re^{6\times6}$ is square and non-singular,

$$K_{joint} = J^T (K_{task} + \sum_i H_i \bar{\tau}_i) J = D_{joint} + \hat{K}_{joint}$$

$$D_{joint} = diag.(K_1, \cdots, K_n)$$

Gait synchronization using the contraction theory





The human and XRL system is modeled as a coupled nonlinear oscillating system that must be synchronized. Using the Contraction Theory, we can guarantee that the system tends towards each other exponentially.

$$\frac{d}{dt}\begin{pmatrix}\delta \mathbf{z}_1\\ \delta \mathbf{z}_2\end{pmatrix} = \begin{pmatrix}\mathbf{F}_1 & \mathbf{G}_1\\ \mathbf{G}_2 & \mathbf{F}_2\end{pmatrix}\begin{pmatrix}\delta \mathbf{z}_1\\ \delta \mathbf{z}_2\end{pmatrix} \quad \text{with} \quad \lambda(\mathbf{F}_1)\,\lambda(\mathbf{F}_2) > \frac{1}{4}\min_{\mathbf{K}>0}\,\sigma^2(\mathbf{K}\mathbf{G}_1 + \mathbf{G}_2^T) \quad \text{uniformly}$$

Summary

Completed:

- Understood DOE's needs and design requirements;
- Designed and fabricated a XRL prototype
  - Use of high-torque wheel motors driven by GaNTFET drivers;
- Reduced actuator torque requirements
  - Exploiting the dual singularity;
  - Null-space control
- Fail-safe control system architecture
  - Single-axis embedded controls can maintain the system stability

Final-Year Plans:

- Human-Robot shared control
  - Hybrid Open-Loop / Closed-Loop Control
- Gait synchronization
  - Contraction theory;
- Human-subject tests
  - IRB has been obtained, but revised
- Technology transfer
  - DOE Waste Management Symposium
  - Interactions with US Steel Worker Union