Experiments with Balancing on Irregular Terrains using the Dreamer Mobile Humanoid Robot



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Robotics Science and Systems

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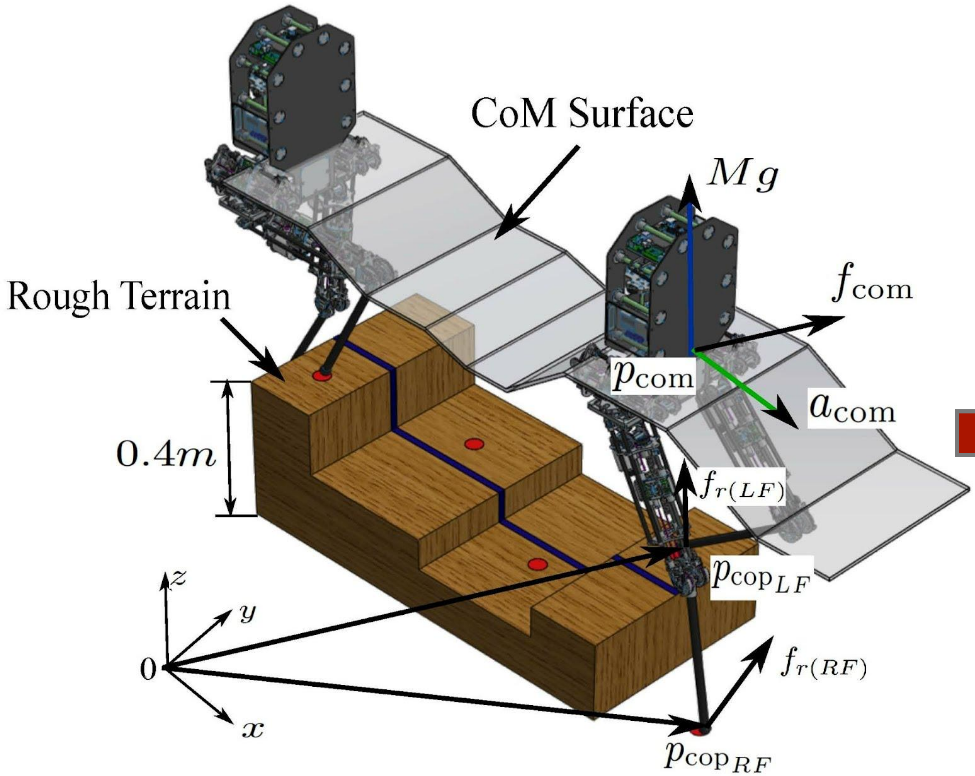
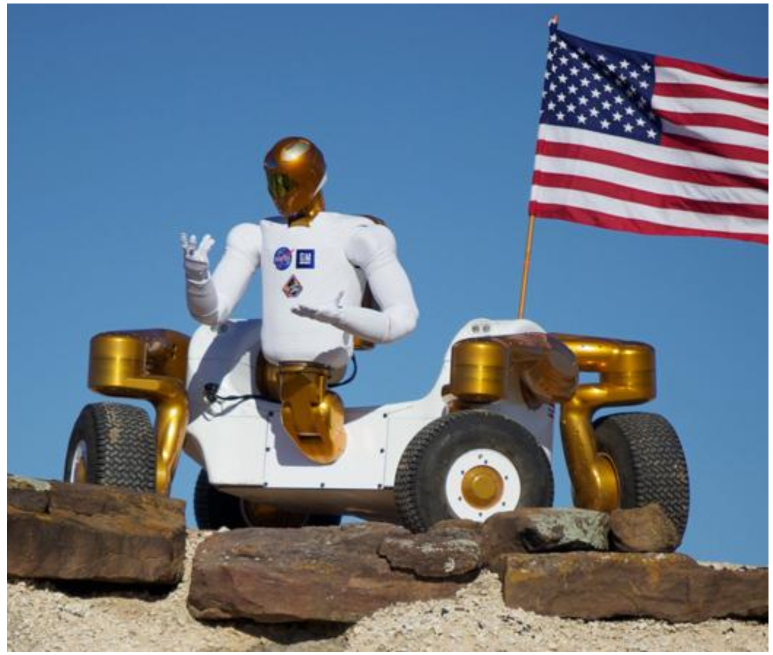
Motivation



Hume Biped Robot Walking in rough terrain [UT Austin]



Centaur 2 Dexterous Base with Robonaut 2 Upper Body Humanoid [NASA JSC]

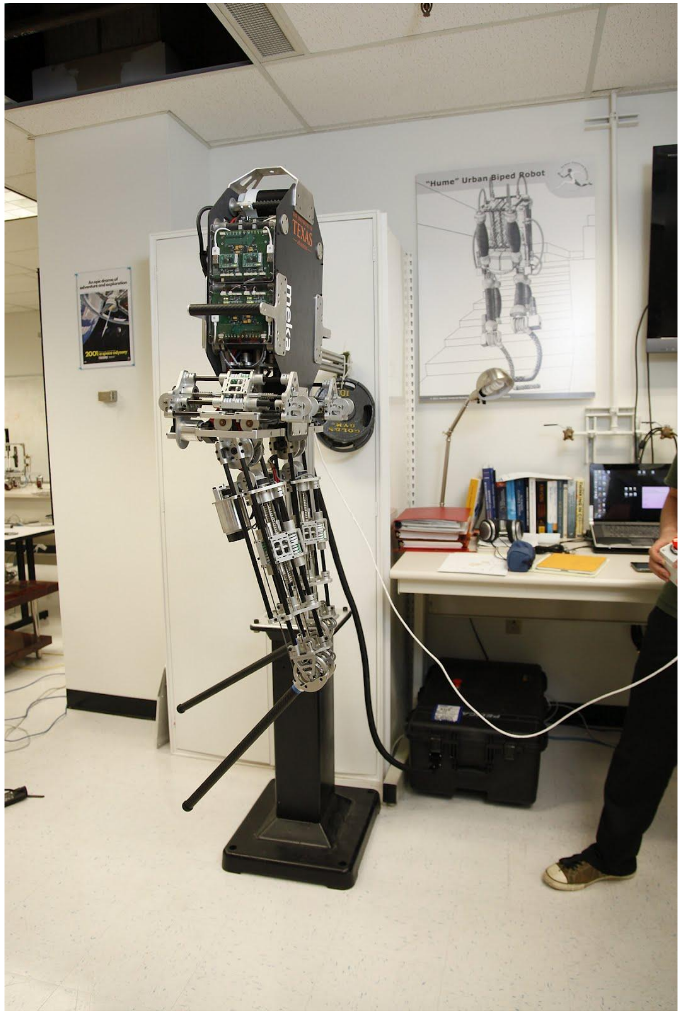
From Simulation to Reality: Whole-Body Multicontact Control

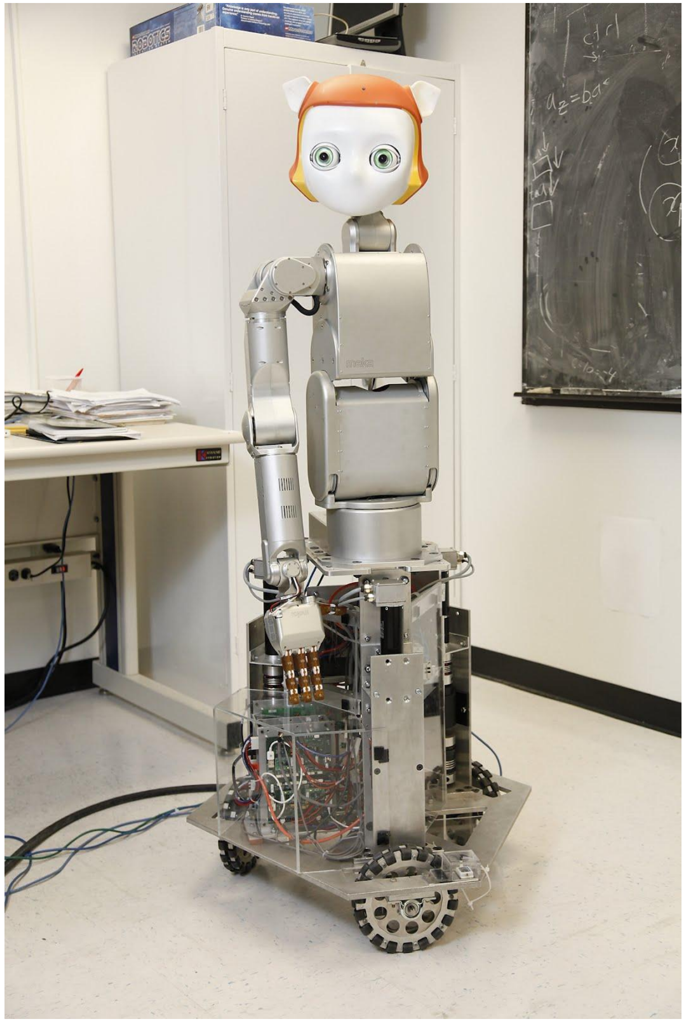
Years 2002-2012

Pursuing Whole-Body Multicontact Control

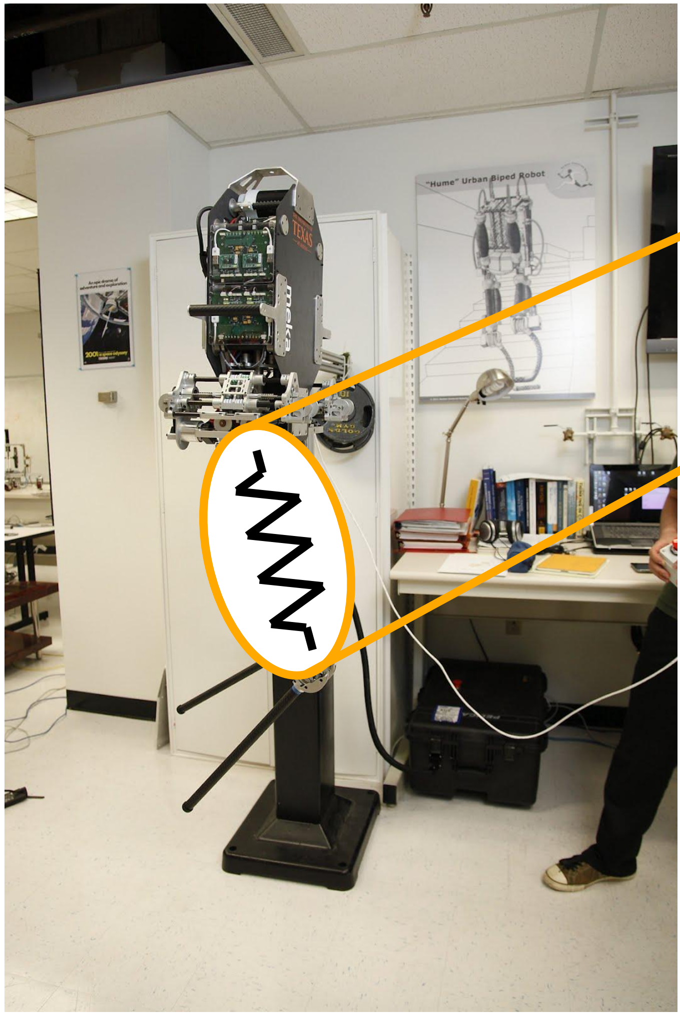
Luis Sentis' Contributions at UT Austin and Stanford University

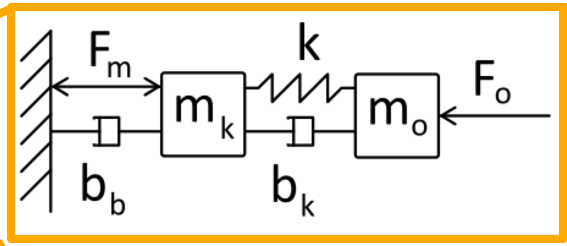
Facilities

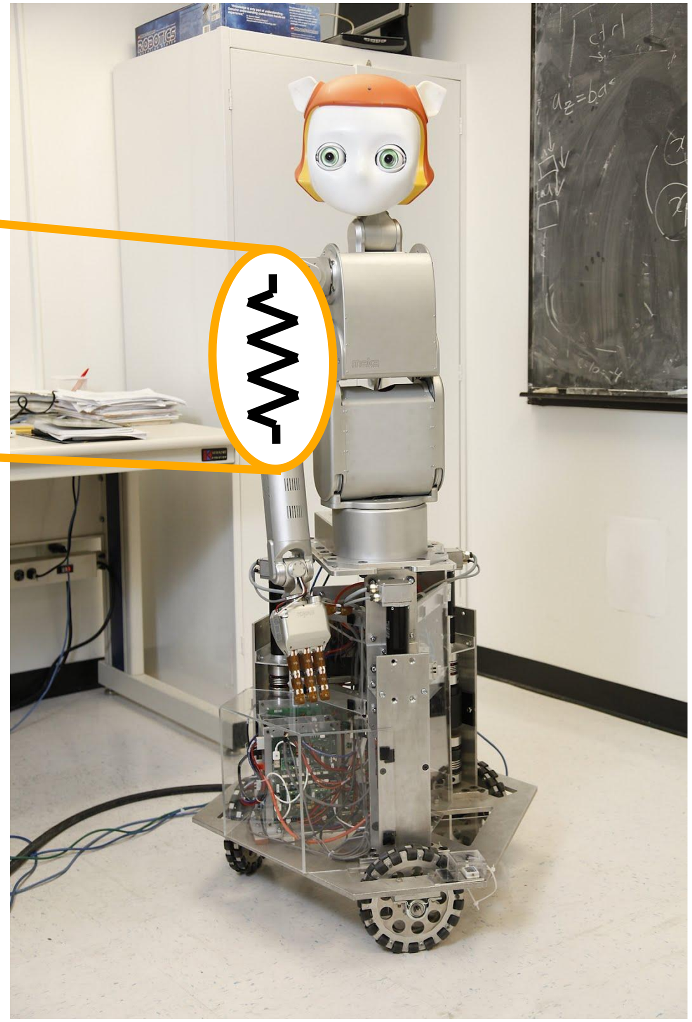




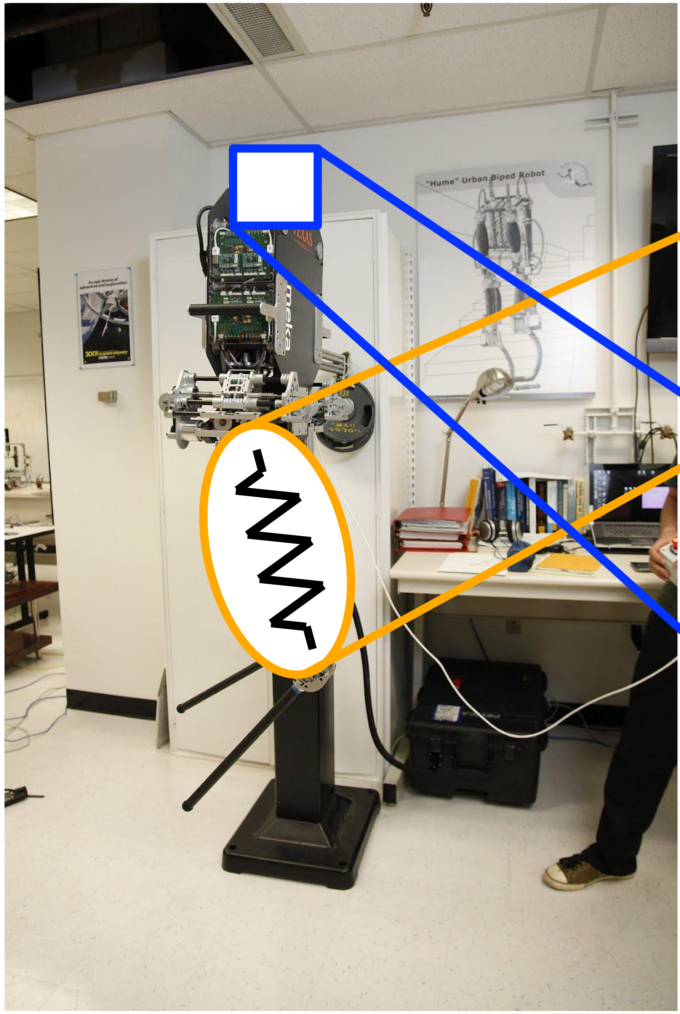
Facilities

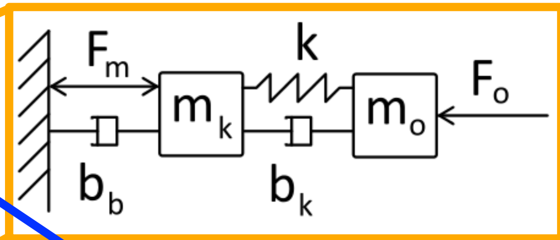






Facilities

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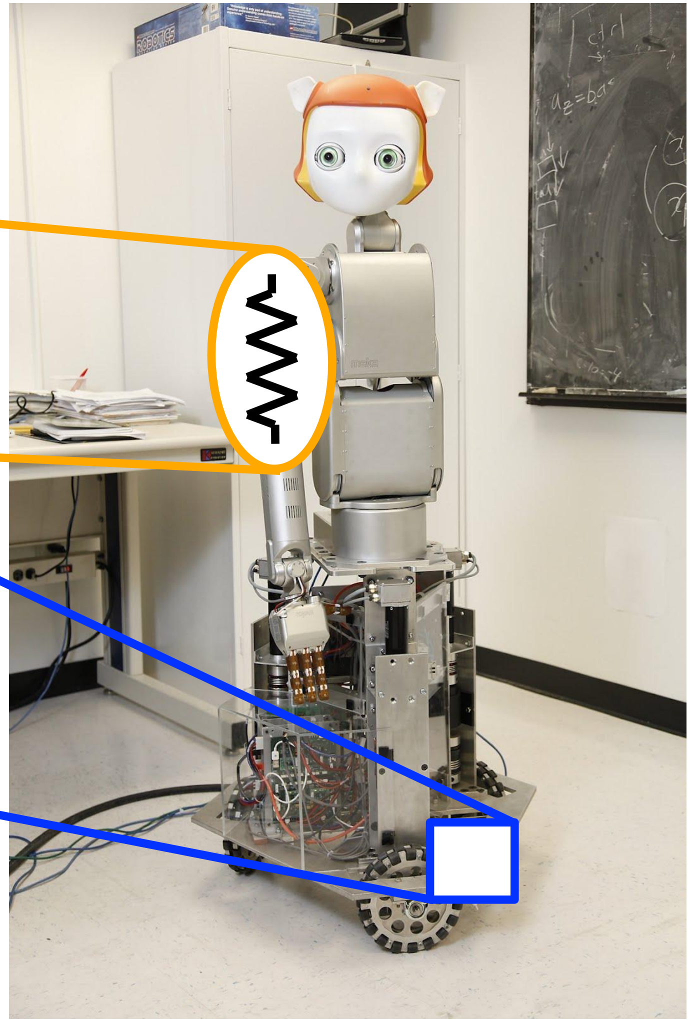
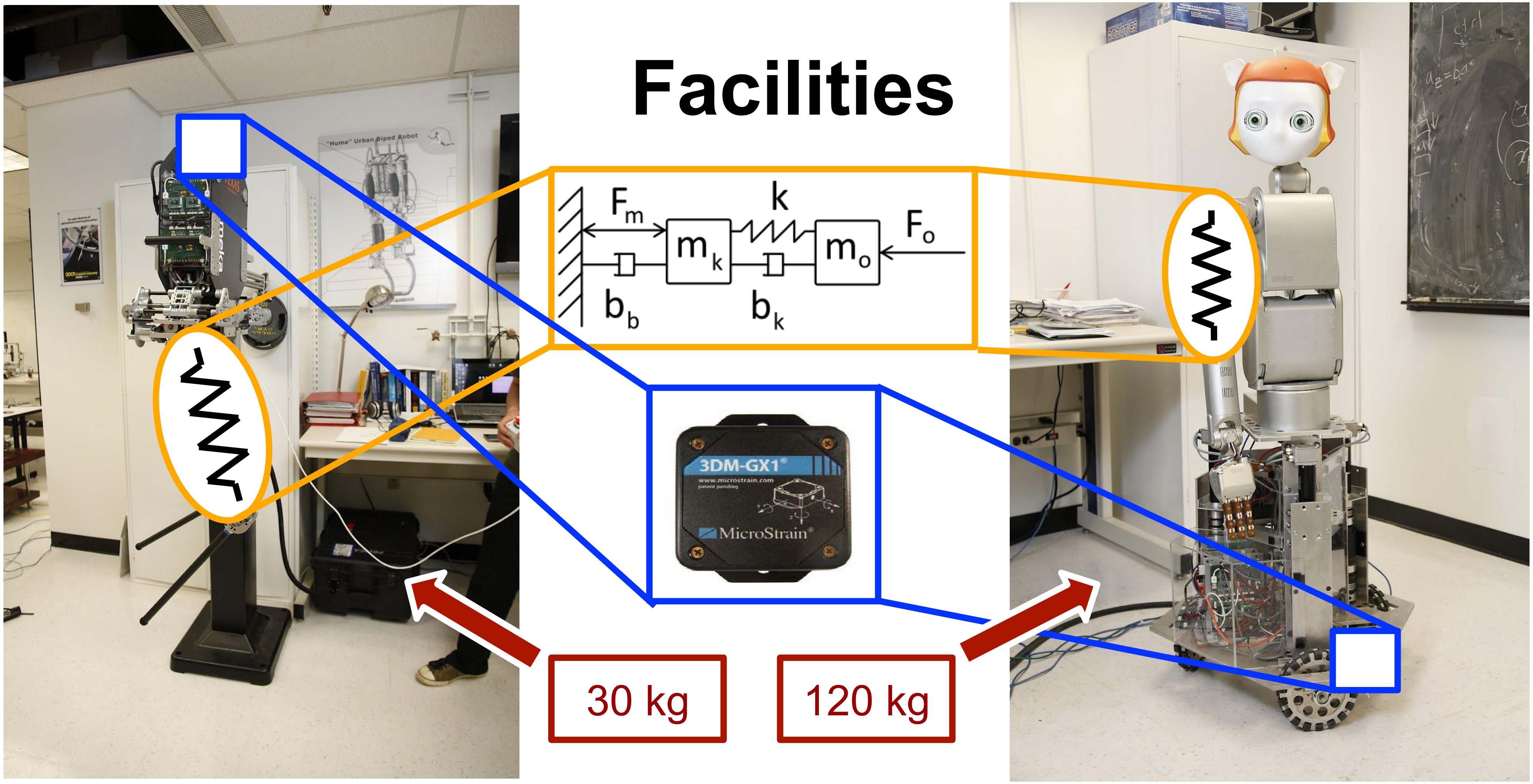
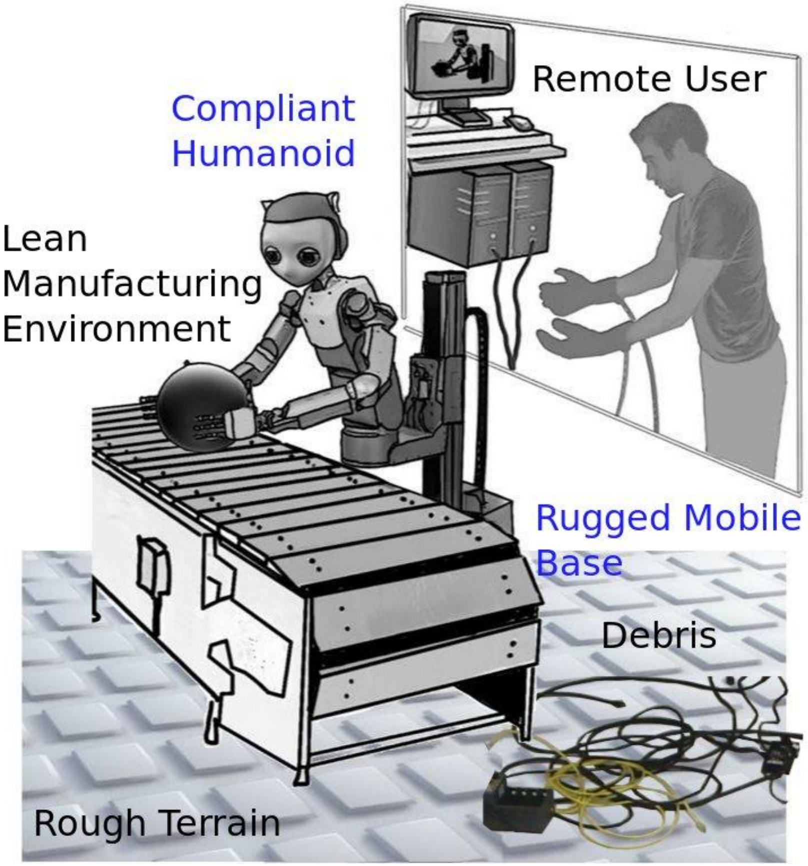
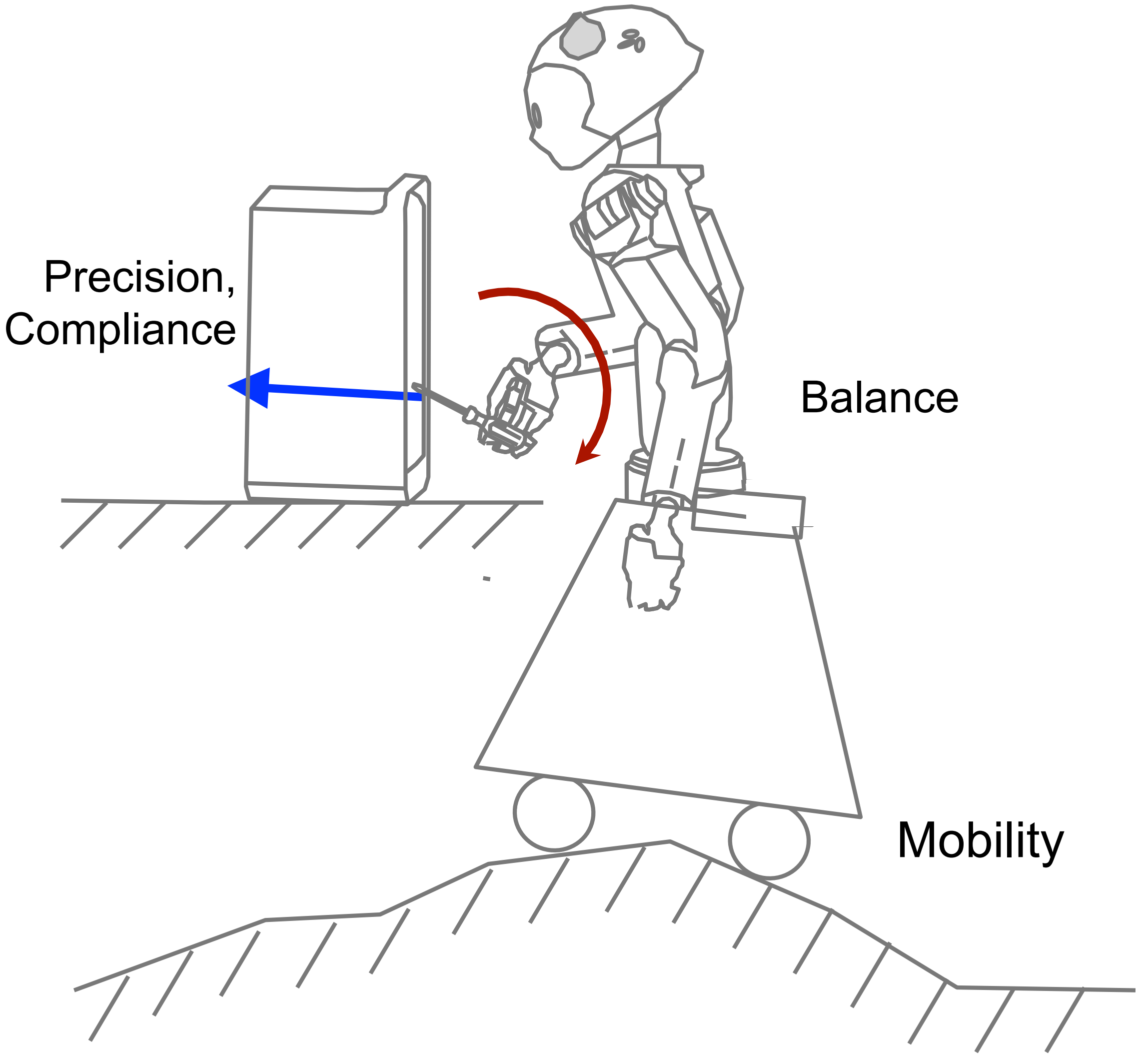


Facilities



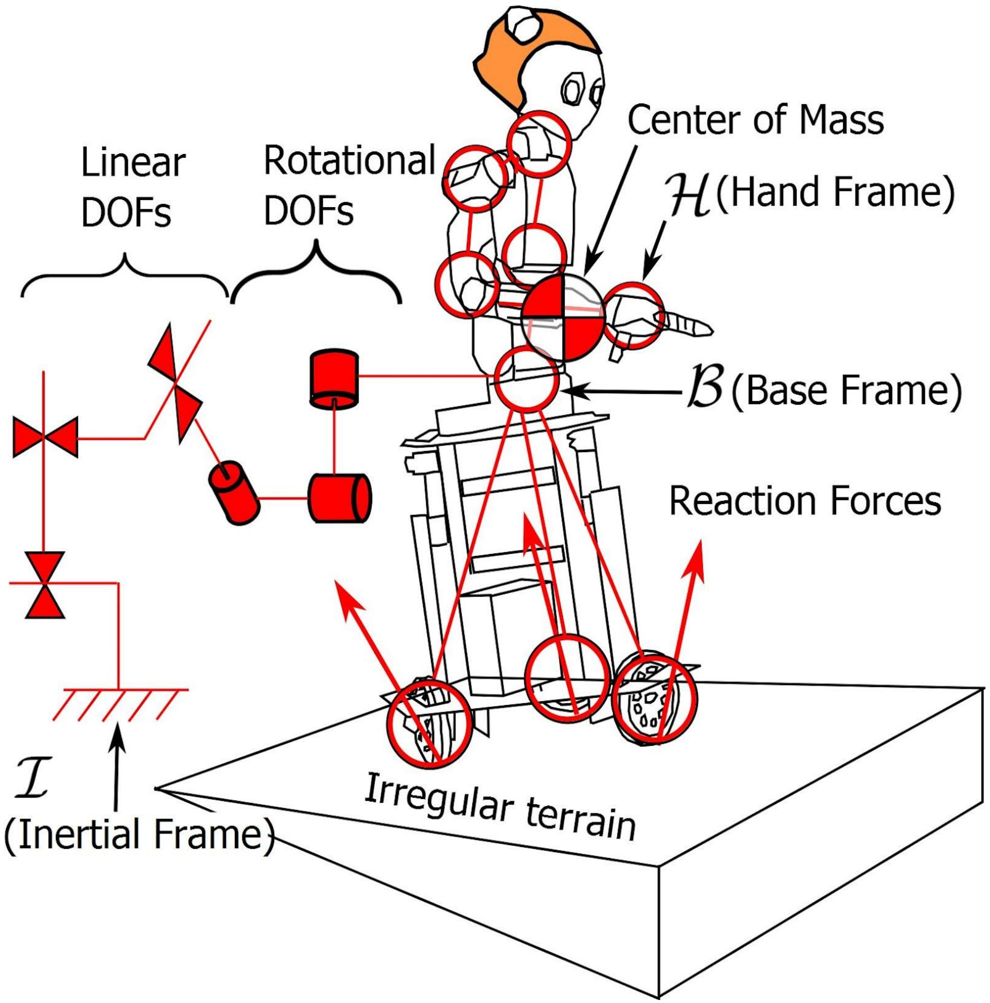
What is Rough Terrain Manipulation?





- Precisely manipulate the environment while adapting to terrain disturbances
- By precision tasks we mean hybrid position/force manipulation

Mechatronics of Dreamer



- 19 Degrees of Freedom
  - 10 DOFs torso/arm (hip coupled to trunk)
  - 3 DOFs holonomic base (triangle of omni wheels)
  - 6 unactuated (free-body dynamics)

- Various Constraints
  - omni wheels
  - supporting contact
  - biarticulate transmission

- Torque control
- Small footprint calls for balance
- Redundancy calls for posture control

Some Observations

Usually, base motions are treated as planar.

- unstated assumption: never lose contact
- "engineered-in" (broad & heavy base)
- but we need to handle contact changes!

Mobile manipulators rarely use balance.

- typically: broad & heavy base
- otherwise: planar assumption (e.g. Segways)

Objectives of the Research

Main Objective:

Understand rough terrain mobility; create operational space controllers; implement real-world demonstration on the rough terrains.

Sub Objectives:

- develop rough terrain constraints leading to holonomic base motion
- implement the required models for real-time control
- prove stability of posture control for the redundancies
- develop operational space balance control

Approach

Project the rigid body dynamics in a manifold that is consistent with internal/external constraints and underactuation.

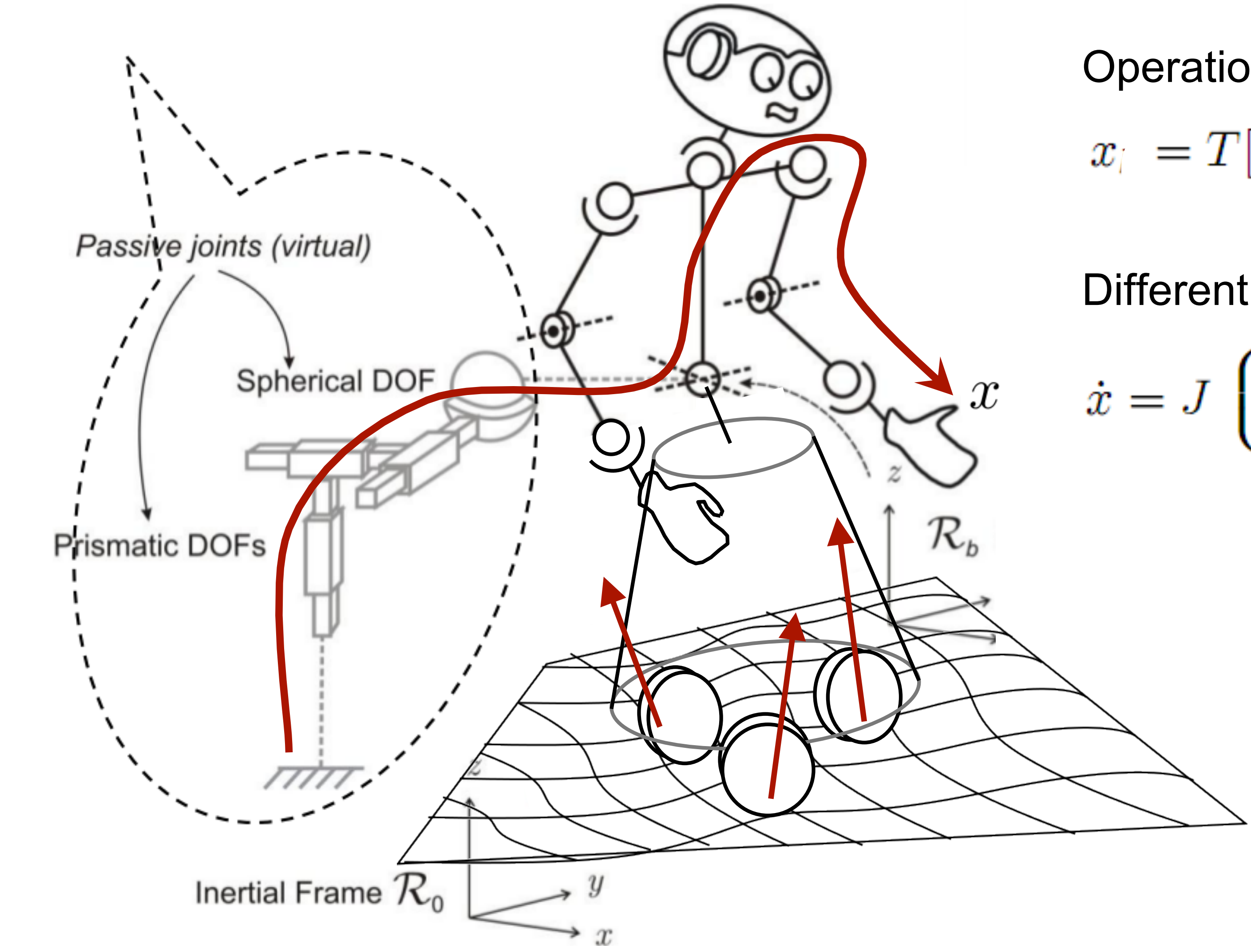
Develop operational space control for rough terrain systems; i.e. express constraints and underactuation via Generalized Jacobians.

Develop skills that can adapt to the environment and can be reused for various manipulation tasks.

Conduct experiments to validate each contribution.

Modeling **Constrained** Free Body Kinematics

(U) Underactuated DOFs



Operational Point (task joints)

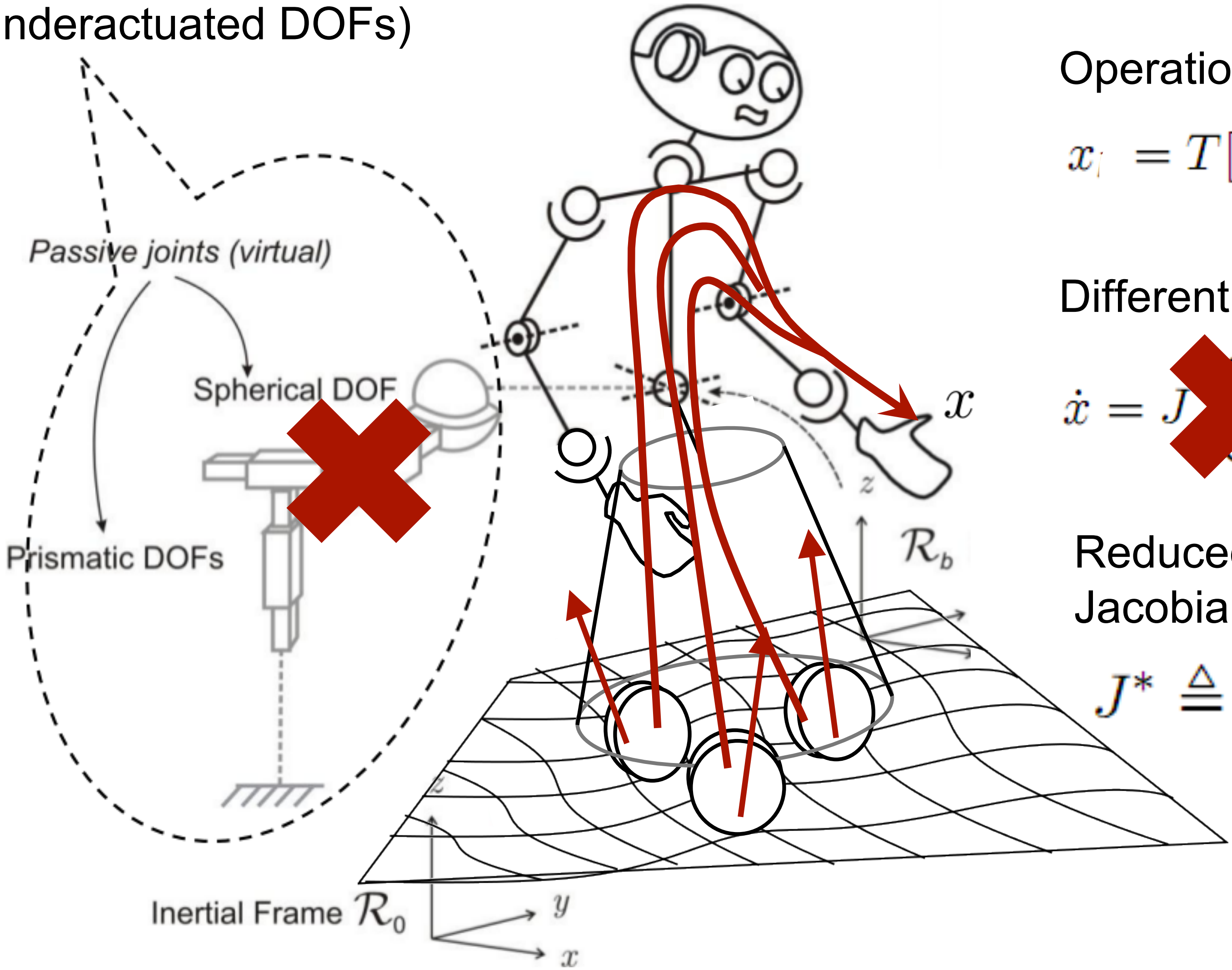
$$x_i = T[x_b, q]$$

Differential Kinematics

$$\dot{x} = J \begin{pmatrix} \vartheta_b \\ \dot{q} \end{pmatrix}$$

Modeling **Constrained** Free Body Kinematics

(U) Non-holonomic Constraints
(Underactuated DOFs)



Operational Point (task joints)

$$x = T[x_b, q]$$

Differential Kinematics

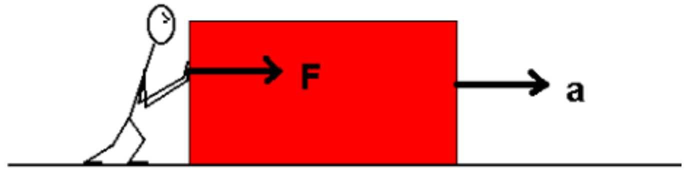
$$\dot{x} = J\,\cancel{[\;]} = J\,\overline{U N_s}\,\dot{q}$$

Reduced constraint consistent Jacobian

$$J^* \triangleq J\,\overline{U N_s}$$

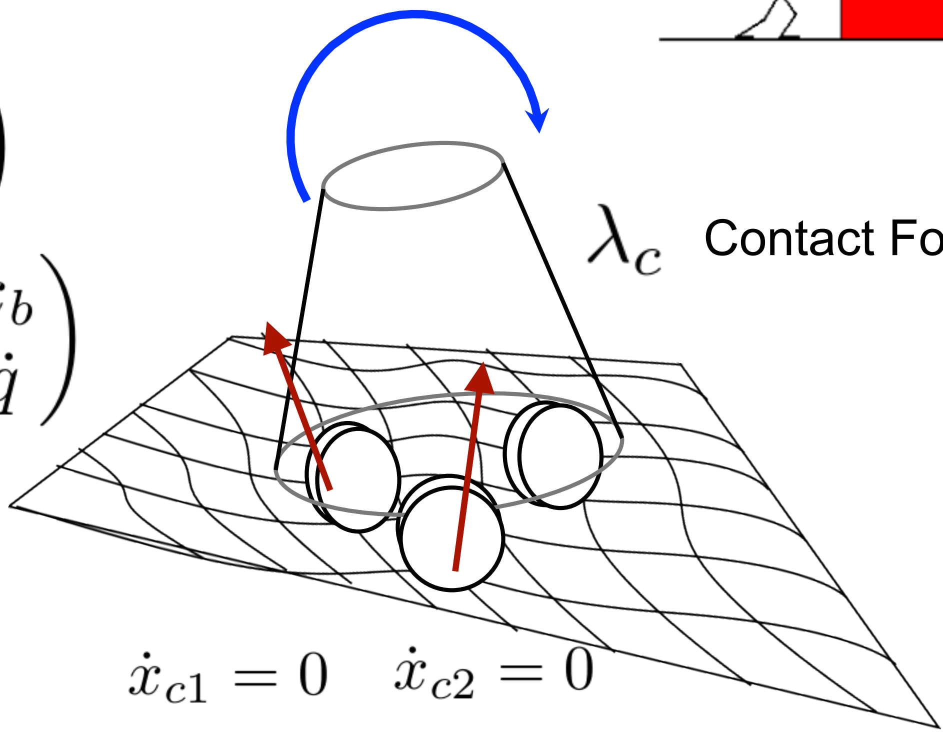
Incorporating Constraints on Dynamics

$$A \begin{pmatrix} \dot{\vartheta}_b \\ \ddot{q} \end{pmatrix} + B + G + J_c^T \lambda_c = \begin{pmatrix} 0_{6\times 1} \\ \Gamma \end{pmatrix}$$



$$x_c = \begin{pmatrix} x_{c1} \\ x_{c2} \end{pmatrix}$$

$$\dot{x}_c = J_c \begin{pmatrix} \dot{x}_b \\ \dot{q} \end{pmatrix}$$



λ_c Contact Forces

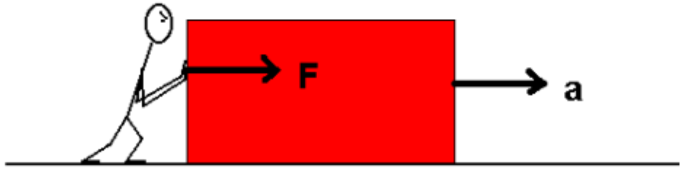
$\dot{x}_{c1} = 0 \quad \dot{x}_{c2} = 0$

Base Mobility Constraints

$$A \begin{pmatrix} \dot{\vartheta}_b \\ \ddot{q} \end{pmatrix} + B + G + J_c^T \lambda_c = \begin{pmatrix} 0_{6\times 1} \\ \Gamma \end{pmatrix}$$

Explicit solution

$$\boxed{\lambda_c = \overline{J}_c^T \left(U^T \Gamma - B - G \right) + \Lambda_c \dot{J}_c \begin{pmatrix} \dot{x}_b \\ \dot{q} \end{pmatrix}}$$



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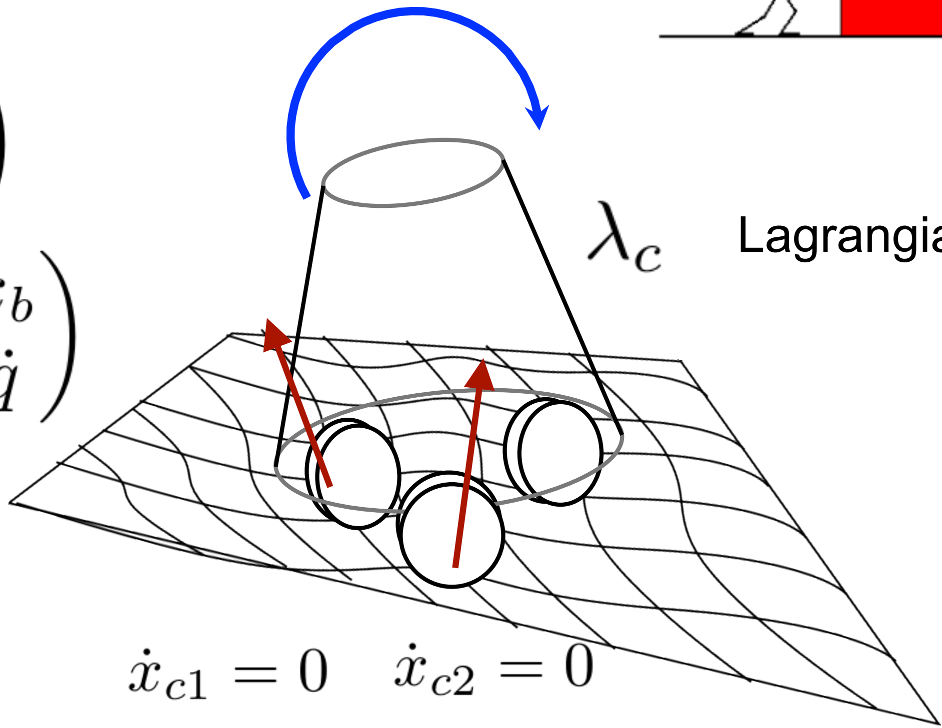


λ_c Lagrangian multipliers

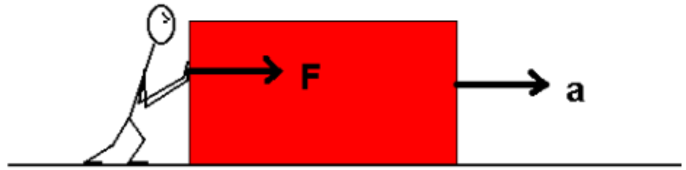
$\dot{x}_{c1} = 0 \quad \dot{x}_{c2} = 0$

Base Mobility Constraints

Implicit solution

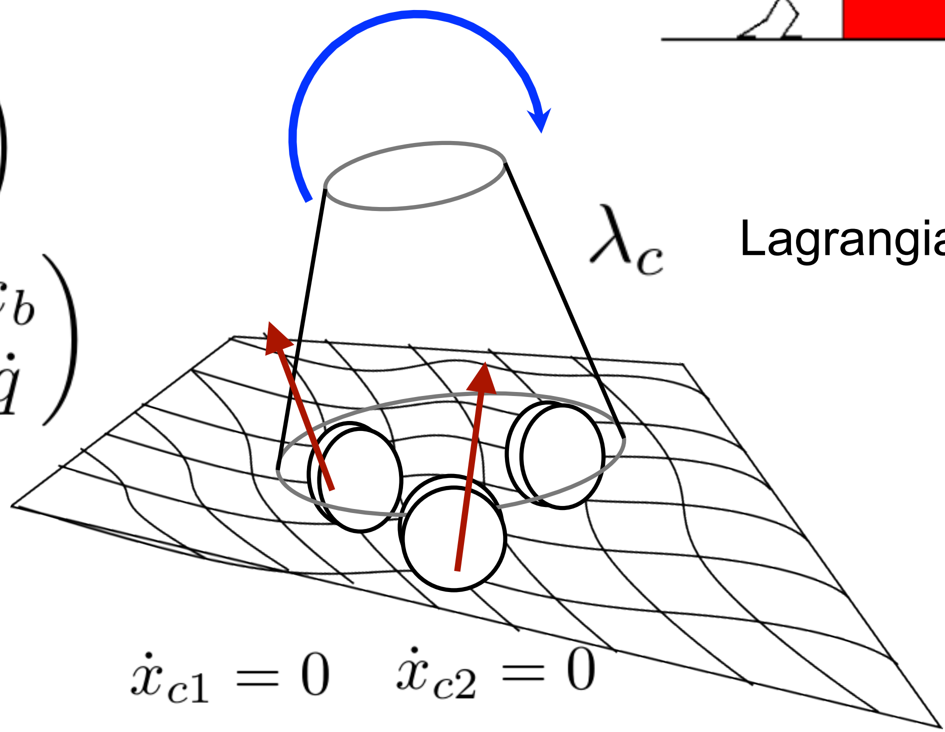
$$\boxed{A \begin{pmatrix} \dot{\vartheta}_b \\ \ddot{q} \end{pmatrix} + N_c^T (B + G) + J_c^T \Lambda_c \dot{J}_c \begin{pmatrix} \vartheta_b \\ \dot{q} \end{pmatrix} = (U\, N_c)^T\, \Gamma}$$

$$\lambda_c = \overline{J}_c^T \left(U^T \Gamma - B - G \right) + \Lambda_c \dot{J}_c \begin{pmatrix} \dot{x}_b \\ \dot{q} \end{pmatrix}$$



$$x_c = \begin{pmatrix} x_{c1} \\ x_{c2} \end{pmatrix}$$

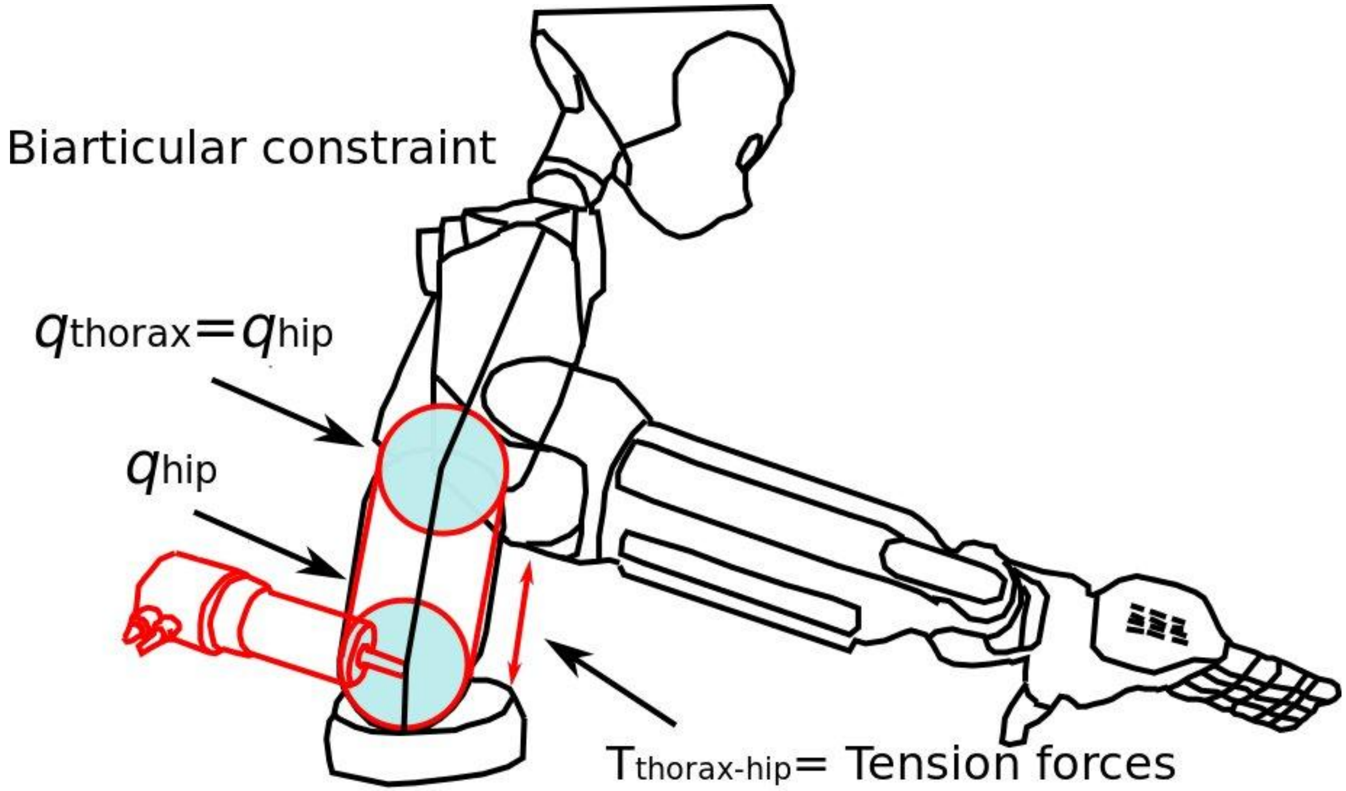
$$\dot{x}_c = J_c \begin{pmatrix} \dot{x}_b \\ \dot{q} \end{pmatrix}$$



λ_c Lagrangian multipliers

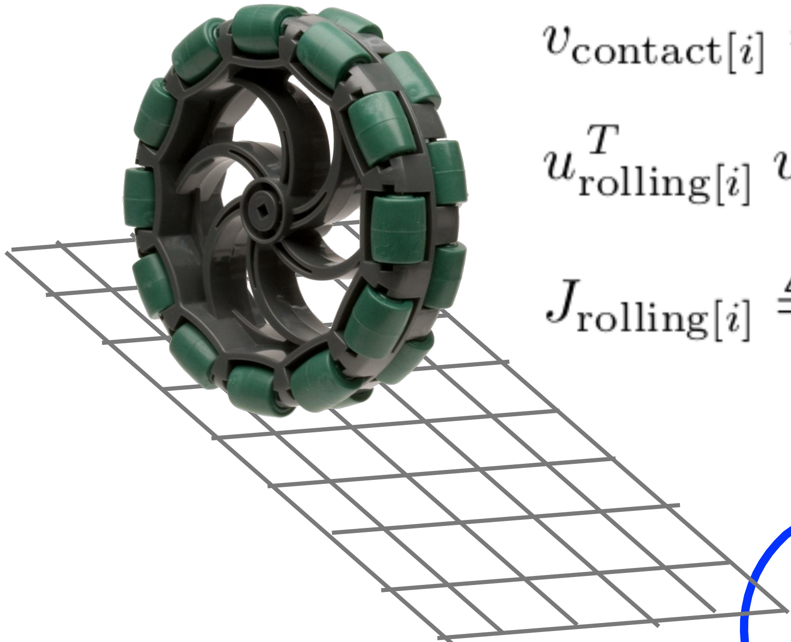
$\dot{x}_{c1} = 0 \quad \dot{x}_{c2} = 0$

Biarticular Transmission Constraints



$$J_{\text{biart}} \triangleq \left([0]_{1\times 6} \; [0]_{1\times 3} \; 0 \; 1 \; -1 \; [0]_{1\times 7} \right) \in \mathbb{R}^{1\times n_{\text{dofs}}}$$

Rolling Constraints (immobile contact)

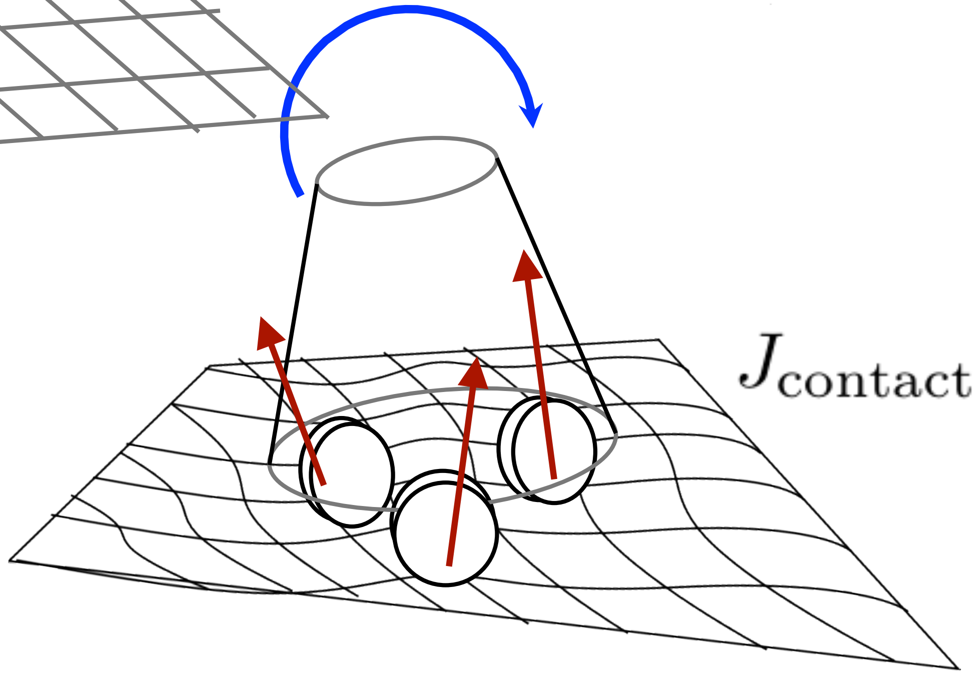


$$v_{\text{contact}[i]} = v_{\text{wheel}[i]} + \omega_{\text{wheel}[i]} \times \delta_{\text{contact}[i]} \in \mathbb{R}^3$$

$$u_{\text{rolling}[i]}^T \; v_{\text{contact}[i]} = 0$$

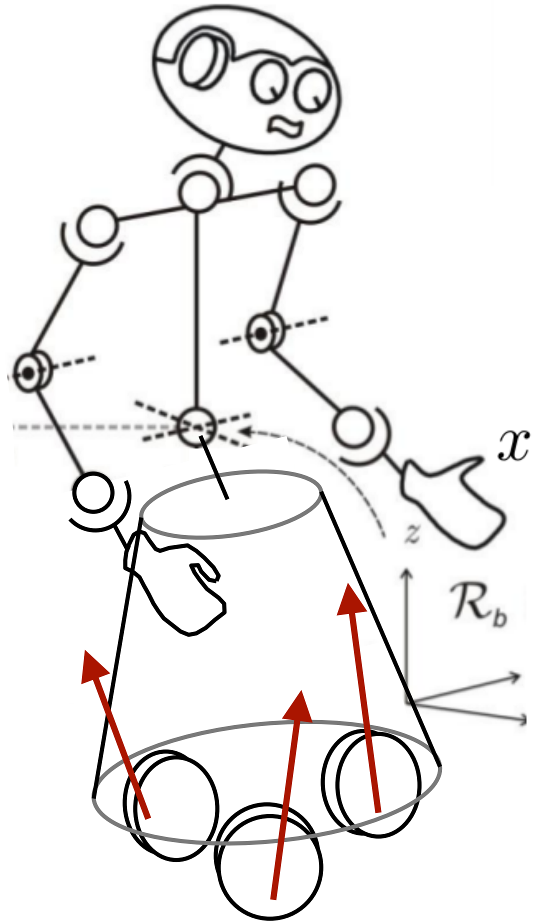
$$J_{\text{rolling}[i]} \triangleq u_{\text{rolling}[i]}^T \left(J_{\text{v,wheel}[i]} - \delta_{\text{contact}[i]} \times J_{\omega,\text{wheel}[i]} \right)$$

$$J_{\text{normal}[i]} \triangleq u_{\text{normal}[i]}^T J_{\text{wheel}}$$

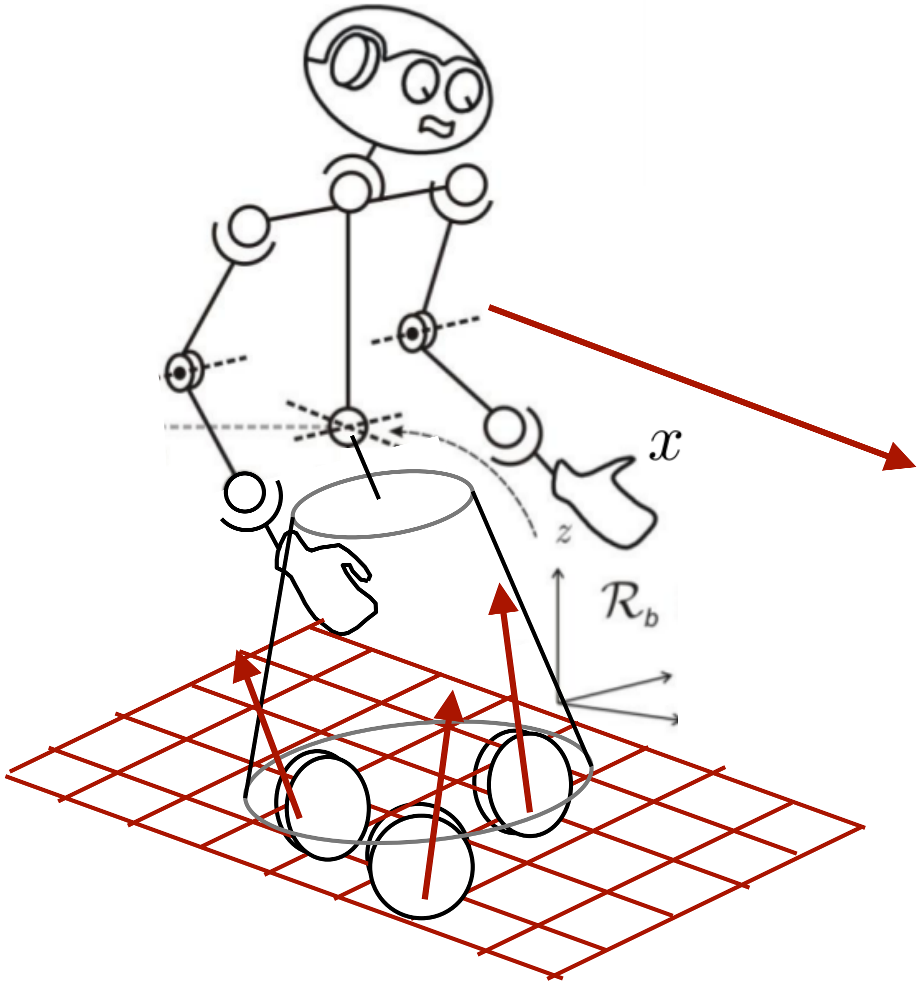


$$J_{\text{contact}} \triangleq \begin{pmatrix} J_{\text{rolling}[1]} \\ J_{\text{rolling}[2]} \\ J_{\text{rolling}[3]} \\ J_{\text{normal}[1]} \\ J_{\text{normal}[2]} \\ J_{\text{normal}[3]} \end{pmatrix} \in \mathbb{R}$$

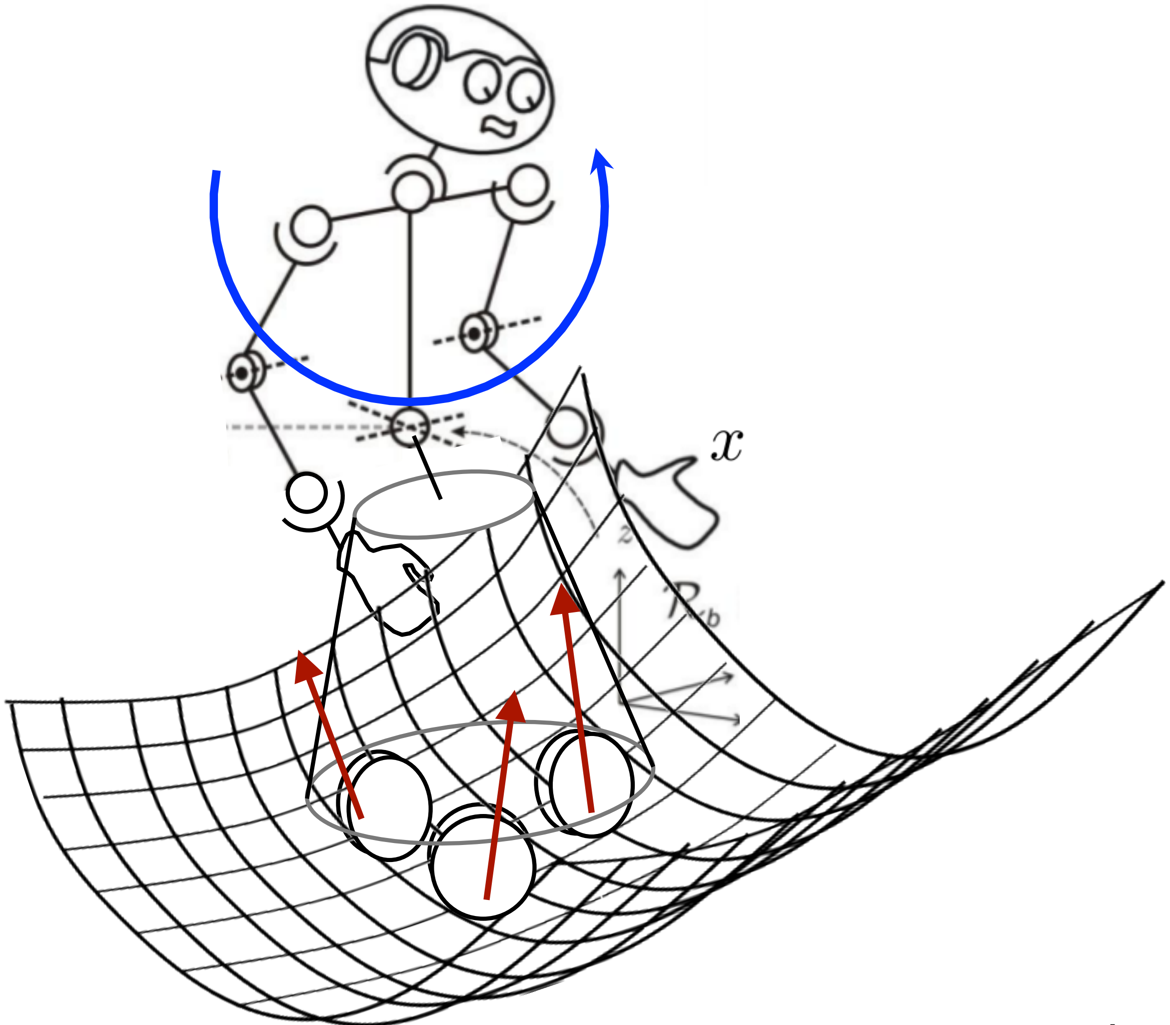
Analysis of Holonomic Motion



Analysis of Holonomic Motion

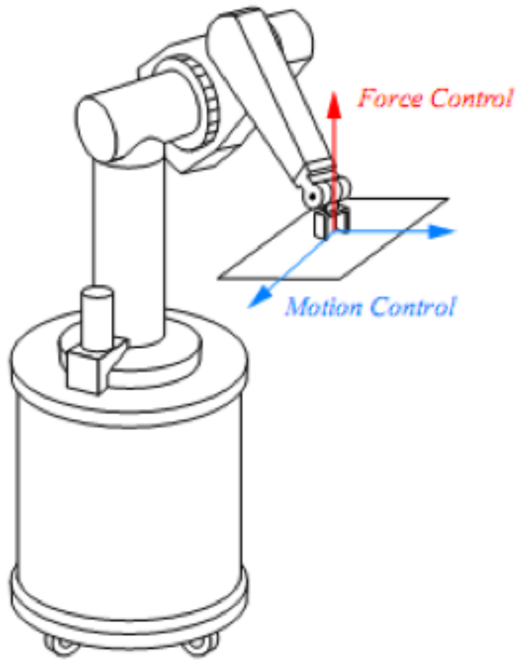


Analysis of Holonomic Motion



…to be studied further…

Operational Space Control



Stanford robotics / AI lab

Control of the task forces (pple virtual work)

$$\Gamma = J_{\text{task}}^{T} F_{\text{task}}$$

Impedance control of task motion

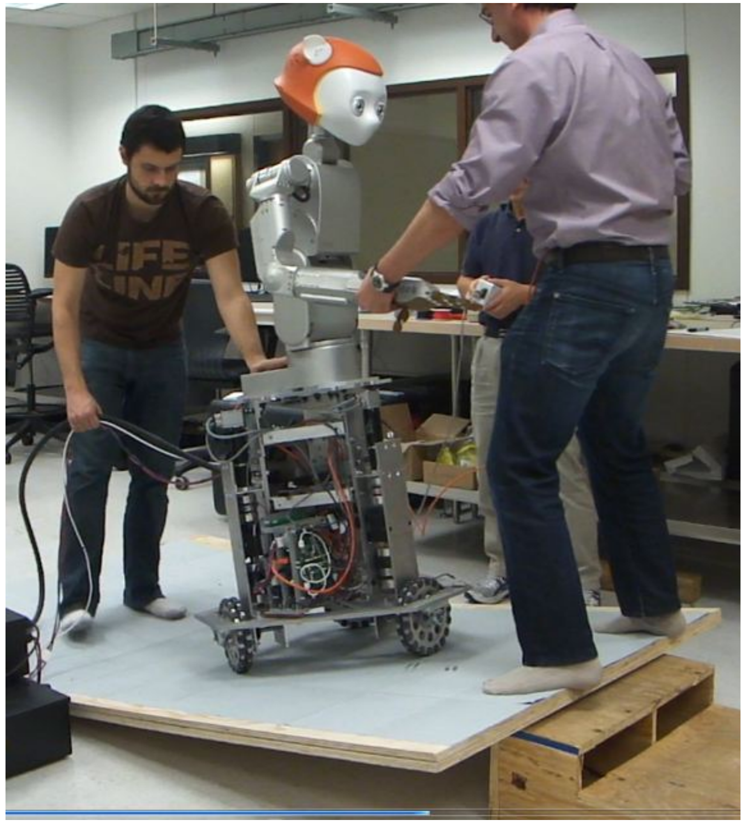
$$F_{\text{task}} = \Lambda_{\text{task}} a_{\text{des}} + \mu_{\text{task}} + p_{\text{task}}$$

Linear Control $\Longrightarrow$ $\ddot{x}_{\text{task}} = a_{\text{des}}$

Potential Fields $\Longrightarrow$ $a_{\text{des}} = -K_p \nabla V_{\text{task}} - K_v \dot{x}_{\text{task}}$

Operational Space Control on Rough Terrains

[Khatib ca 1998]

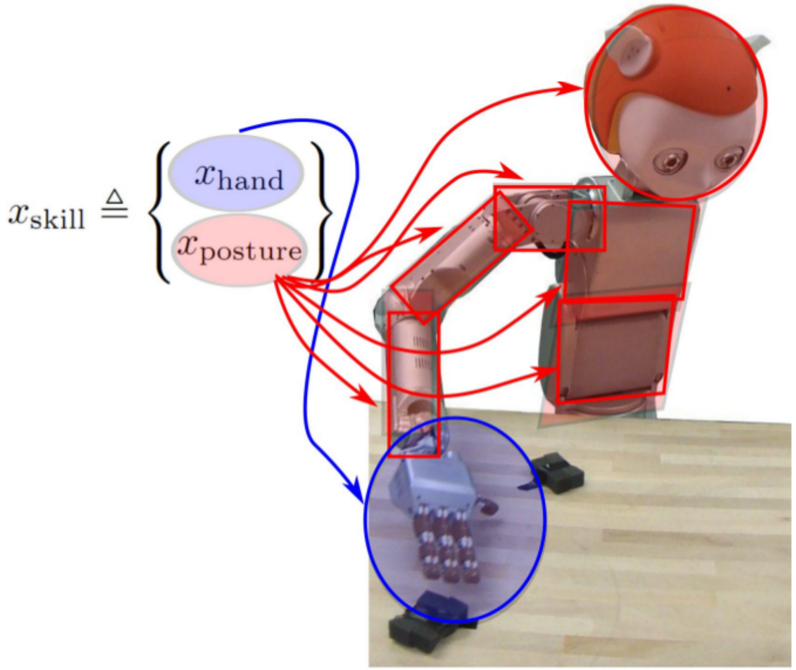


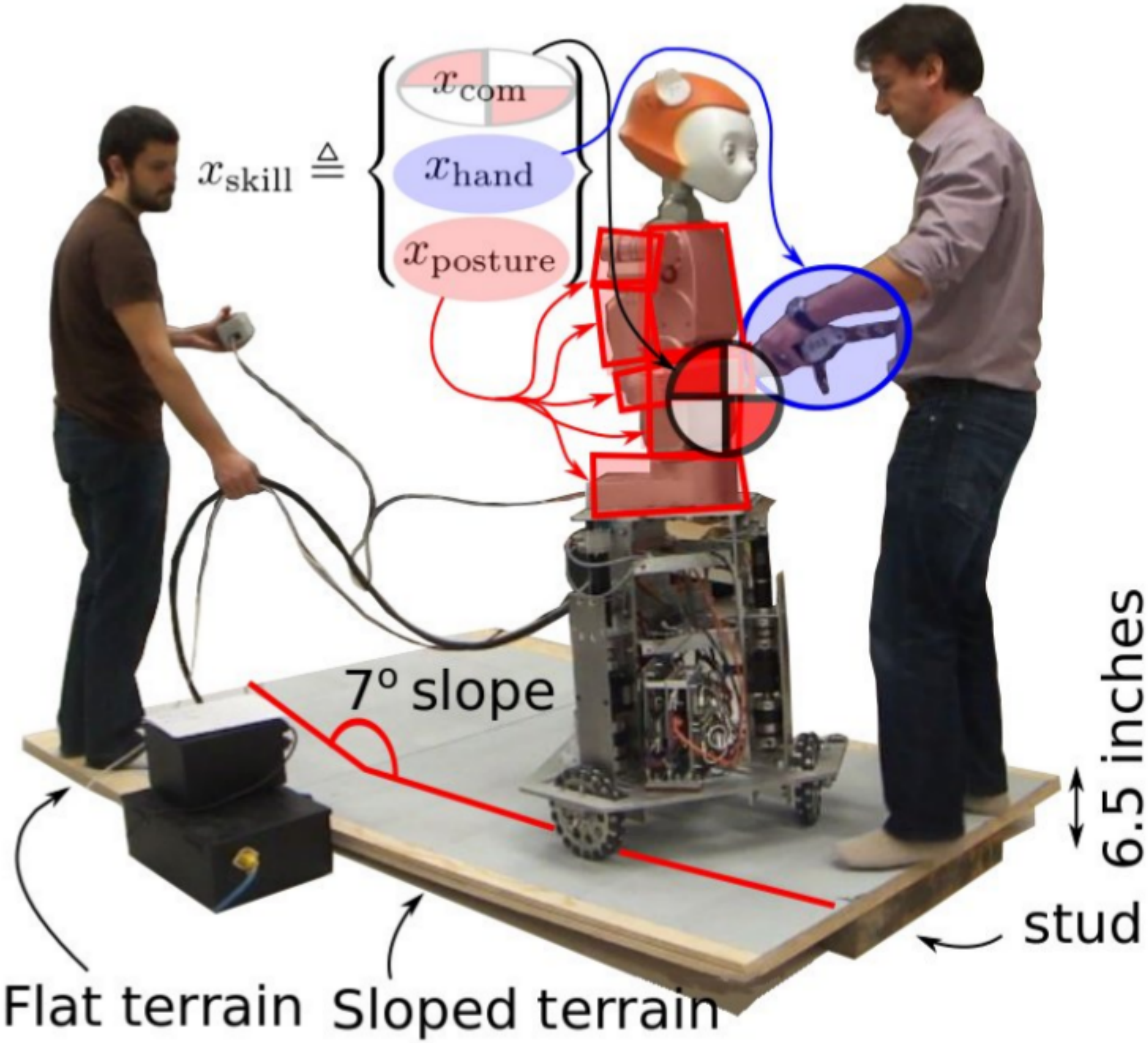
$$\Gamma = J^T F + N^T \Gamma_p$$

$$\Gamma = J^{*T} F + N^{*T} \Gamma_p$$

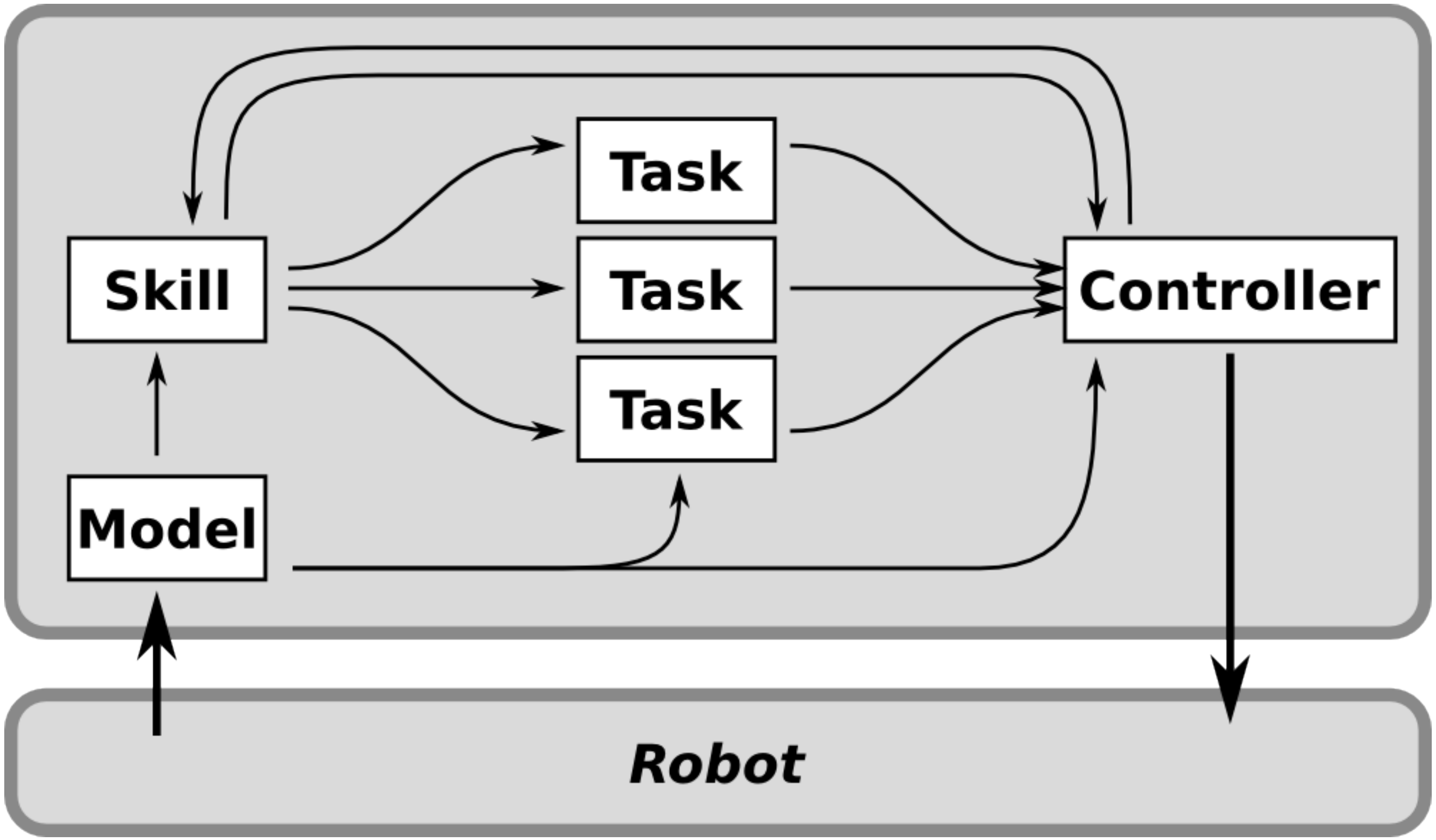
Can be generalized to any number of “**tasks**”…

Skills for Experiments with Dreamer

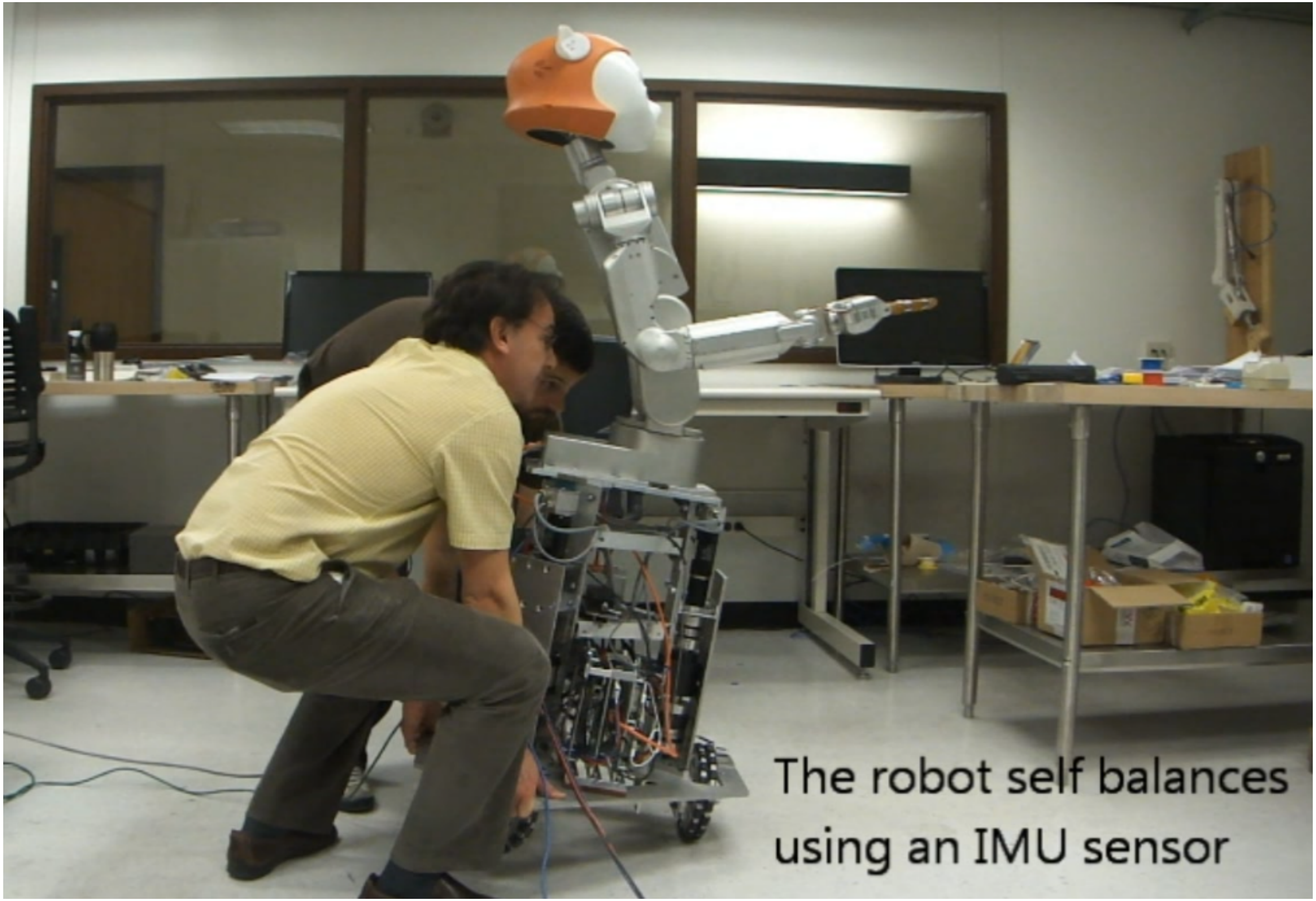




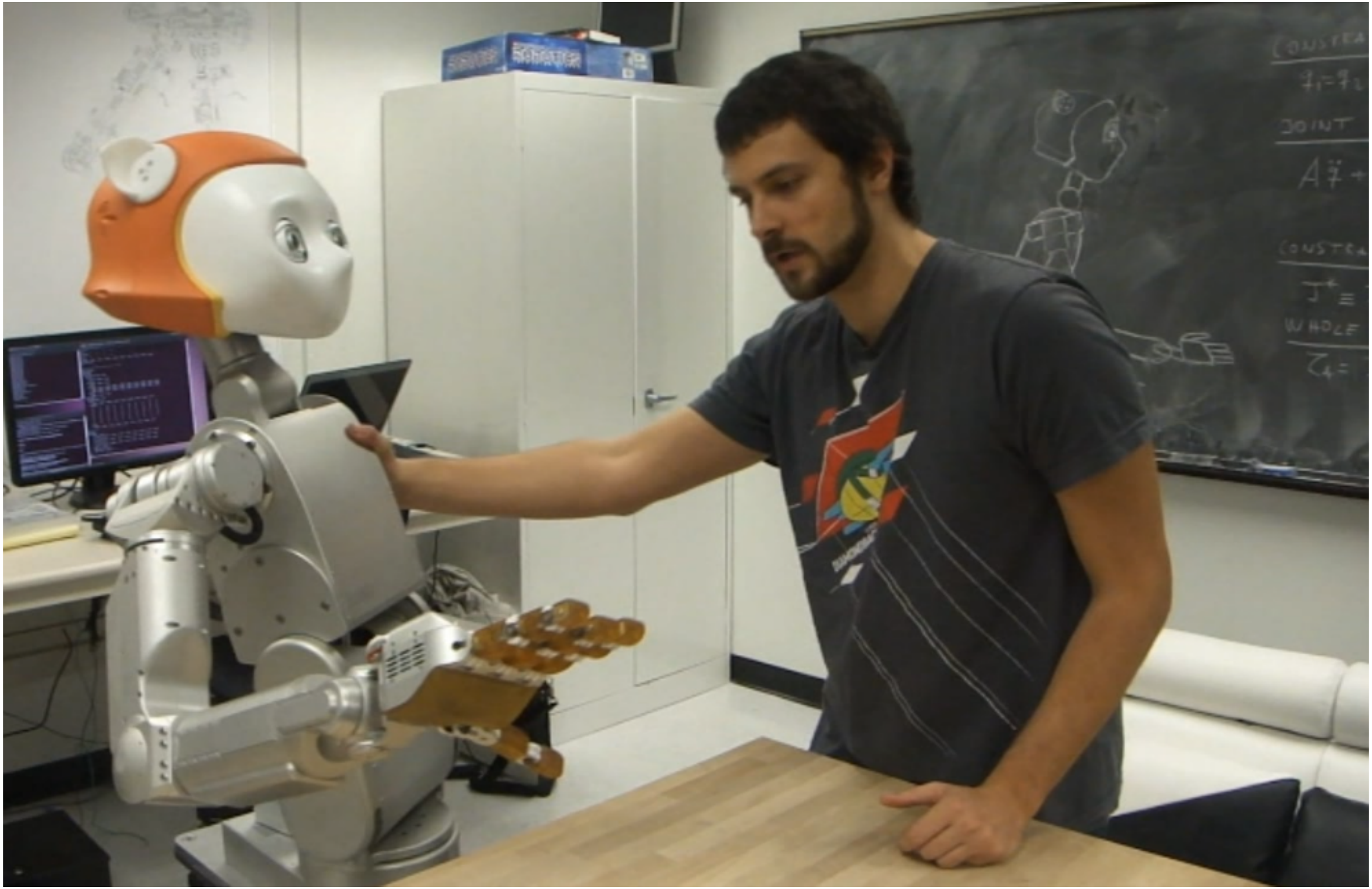
Software Architecture



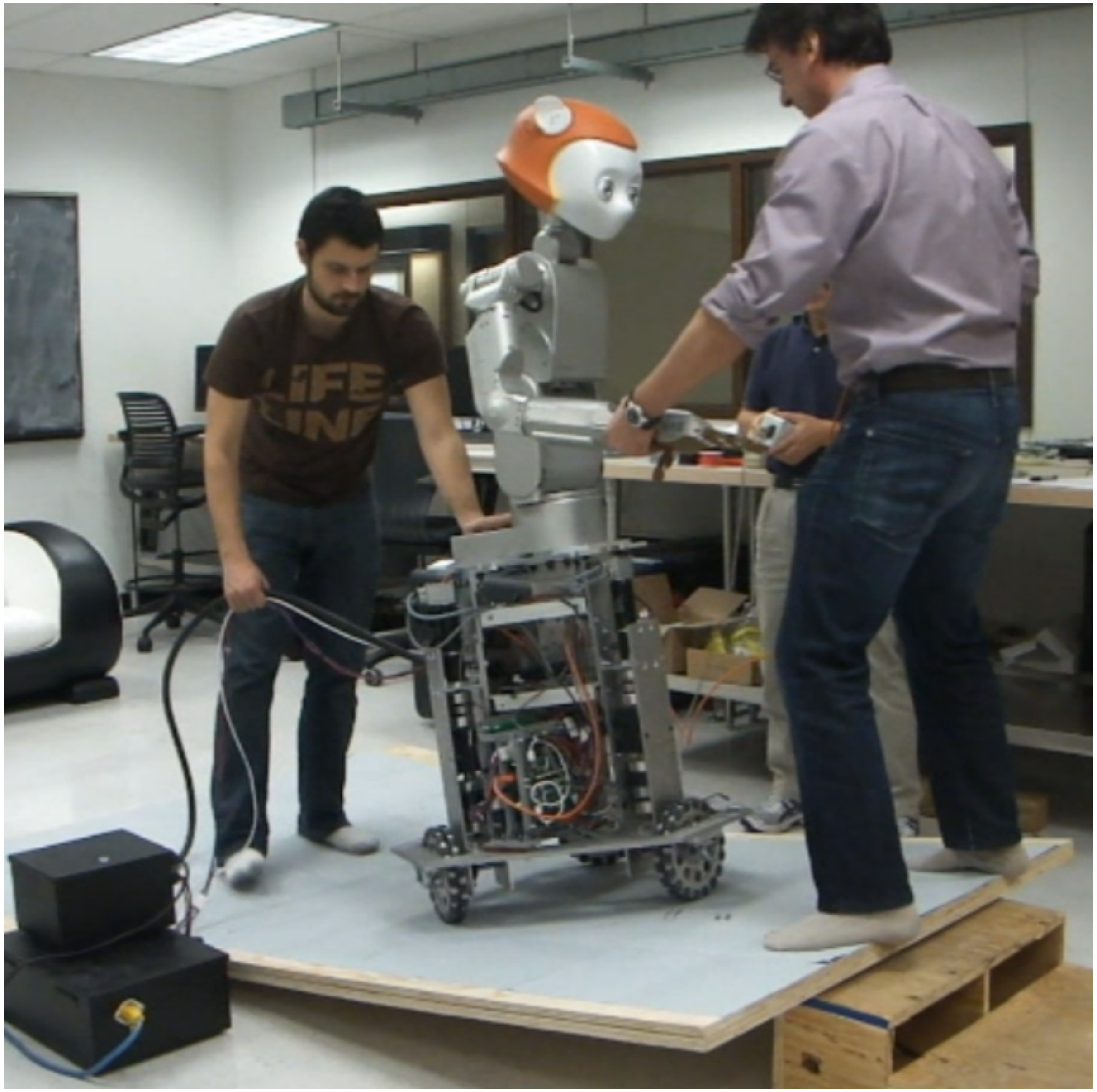
Experiment 1: Balancing



Experiment 2: Reaching



Experiment 3: Rough Terrain Kinesthetic Interaction



Conclusions

- Rough terrain manipulation will allow mobile humanoids to work…
  - + outdoors
  - + in flexible manufacturing
  - + in houses, *etc*

- We need models that characterize the roughness of the terrain.
  - + new interpretation of holonomic mobility

- Operational space whole-body control can be easily extended to provide compliant control for mobile manipulation in rough terrains.

- Real-time capability for 19 DOF robot using off-the-shelf PC

Outlook

- changing contact
- dynamic balance
- study conditions for holonomicities
- build a collection of reusable skills

Thank You!