Constrained Motion Strategies for Robotic Systems

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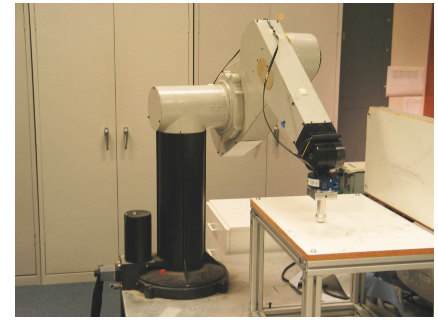
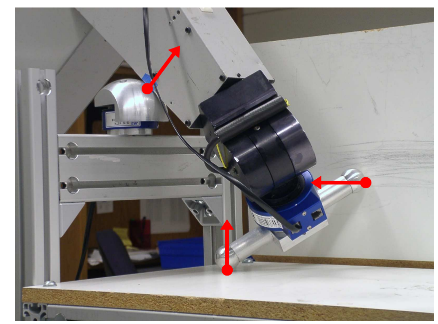
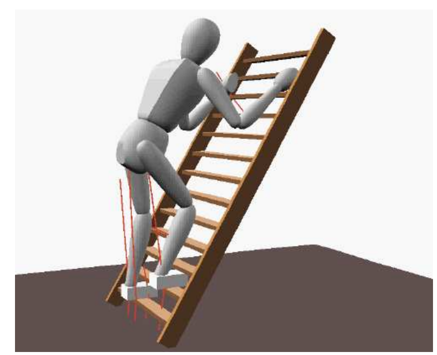
Contributions

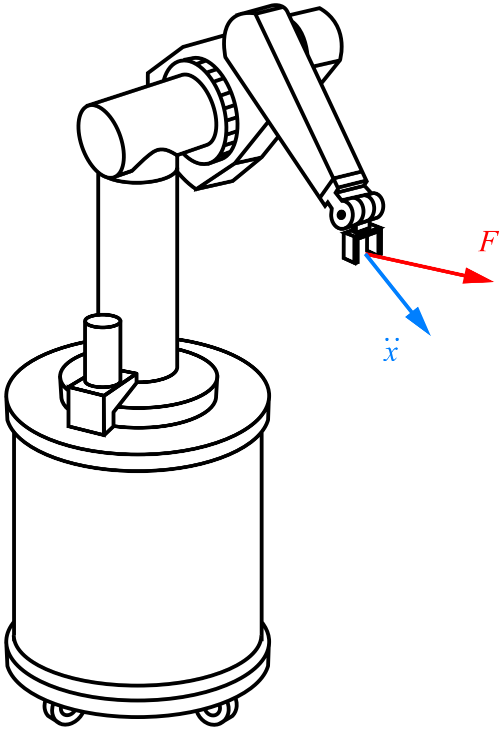
- Robust force control for multi-body robotic systems
  - High fidelity haptically augmented teleoperation
- Development of generalized motion/force control structure for multi-link multi-contact
- Contact force consistent motion/force control strategy for humanoid systems







Motion Control

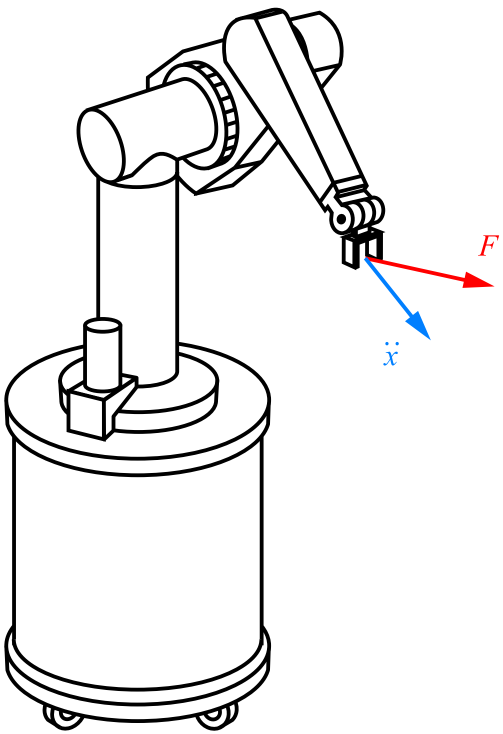


The operational space formulation (Khatib 87)

Equations of motion in joint space

$$A\ddot{q} + b(q, \dot{q}) + g(q) = \Gamma$$

Motion Control



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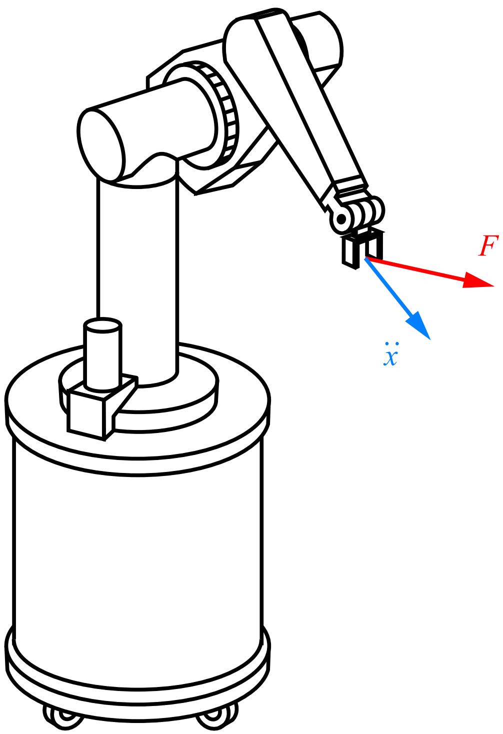
Dynamics in the operational space

$$\Lambda\ddot{x} + \mu(q, \dot{q}) + p(q) = F$$

Motion Control



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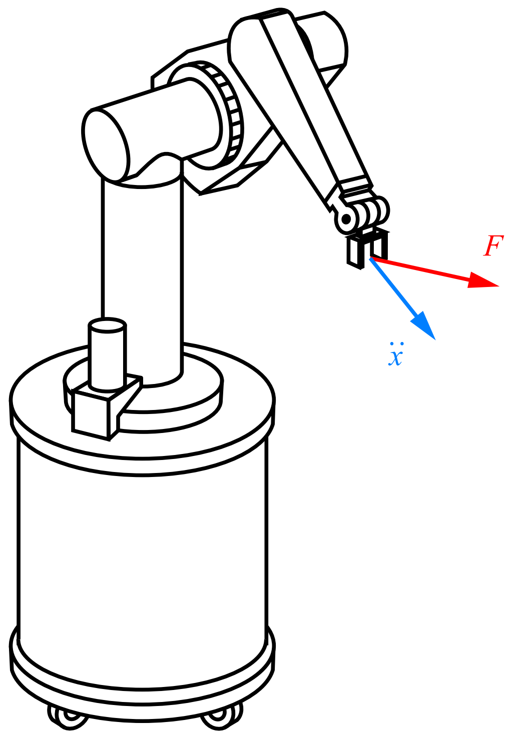

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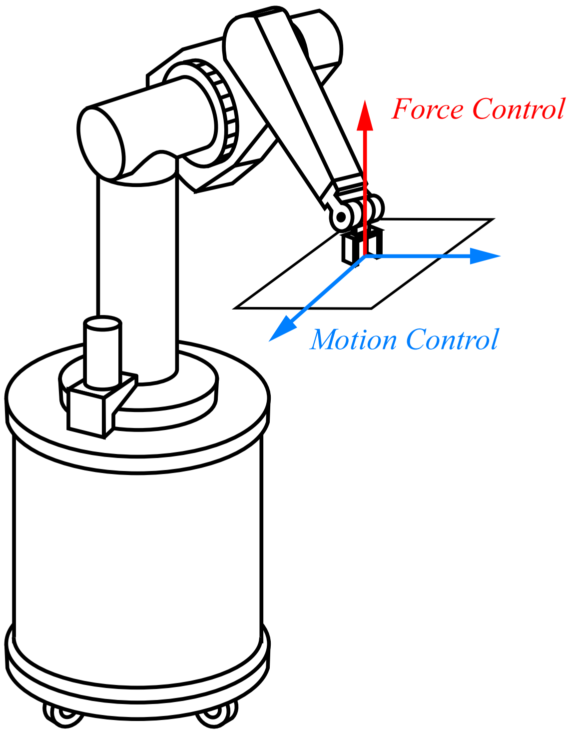
The operational space formulation was extended to handle multiple points (Russakow, Khatib, and Rock 1995)

$x = [x_1, x_2, \ldots, x_m]^T$

Motion/Force Control

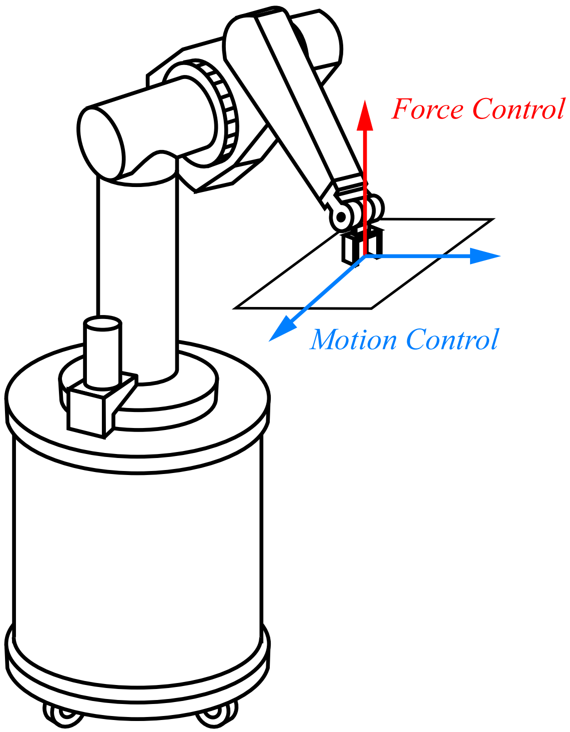


Control force

$$F = \hat{\Lambda} f^* + \hat{\mu}(q, \dot{q}) + \hat{p}(q) + \hat{f}_c$$

Compliant frame selection matrix Ω_f and Ω_m (Raibert and Craig 81, Khatib 87)

Motion/Force Control



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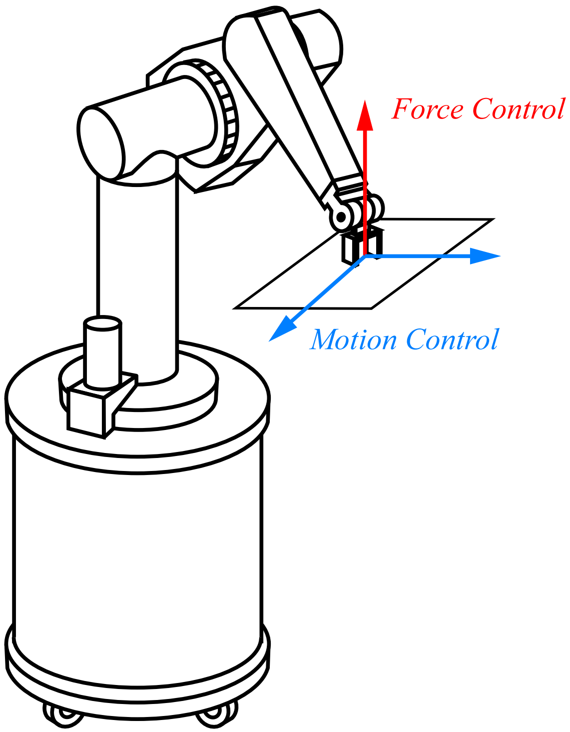
$$f^* = \Omega_f f_f^* + \Omega_m f_m^*$$

Motion/Force Control



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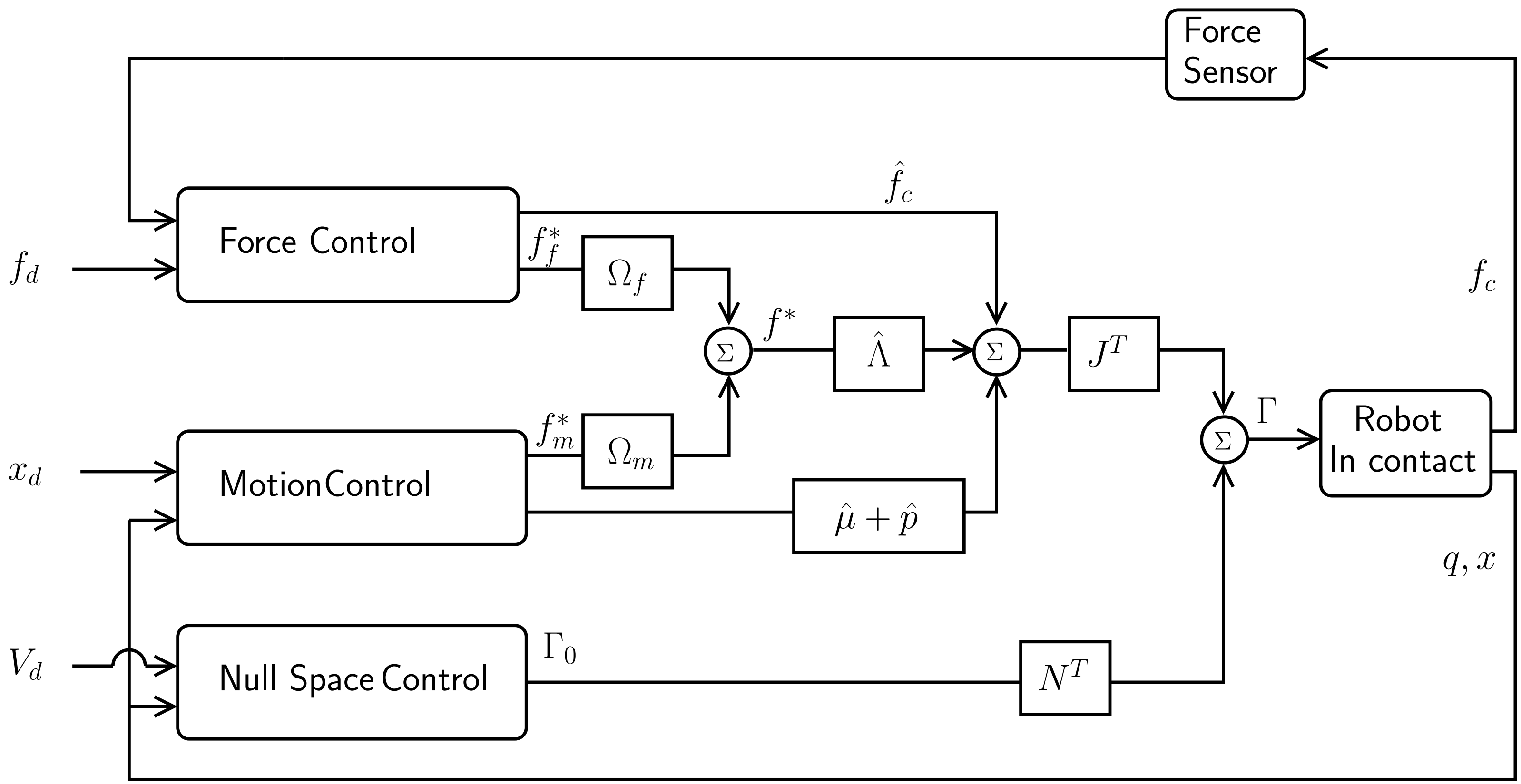
Compliant frame selection matrix Ω_f and Ω_m (Raibert and Craig 81, Khatib 87)

$$f^* = \Omega_f f_f^* + \Omega_m f_m^*$$

With environmental model (stiffness k_s),

$$\begin{cases} \ddot{x}_m &= f_m^* \\ \frac{1}{k_s} \ddot{f}_c &= f_f^* \end{cases}$$

Motion/Force Control Framework



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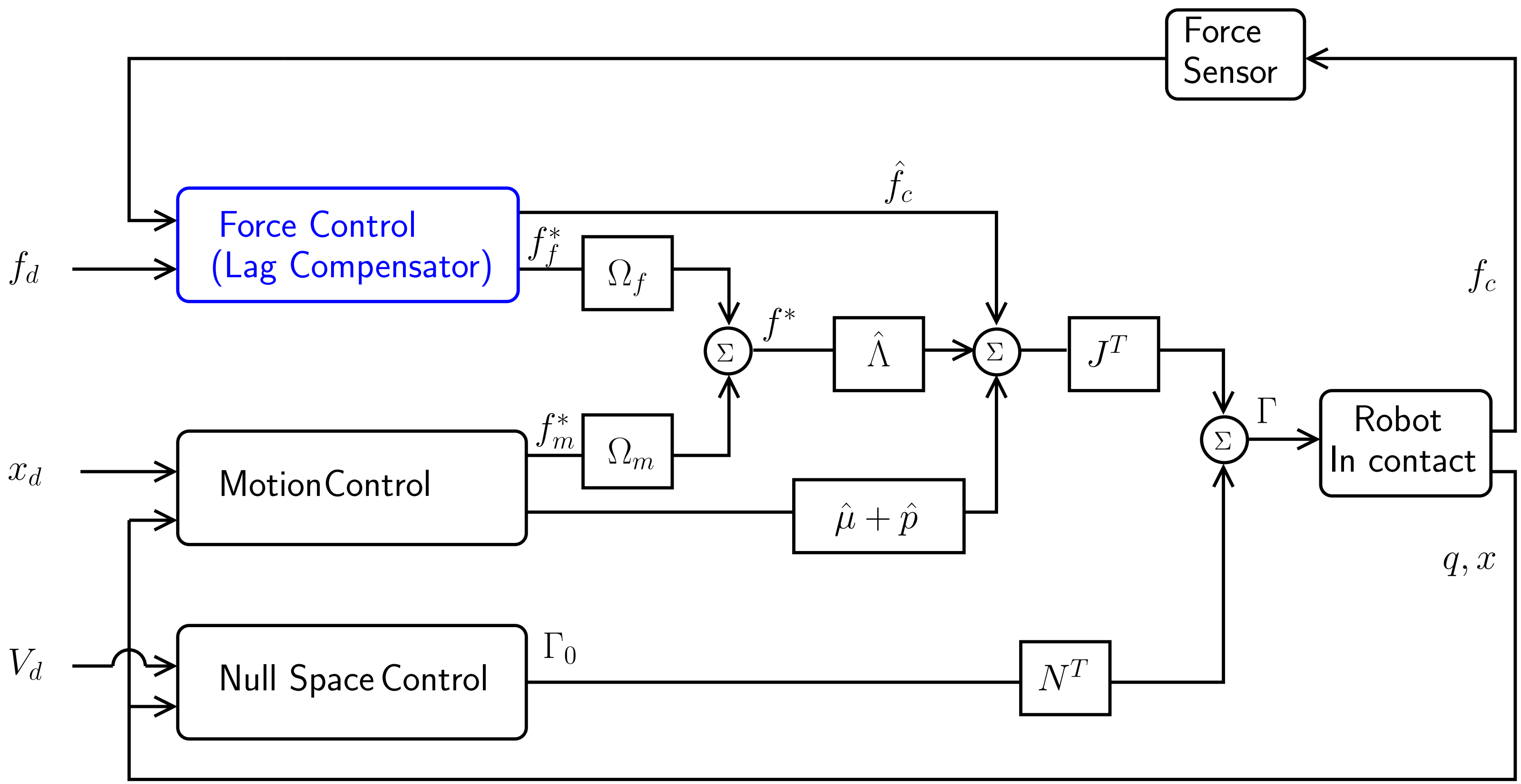
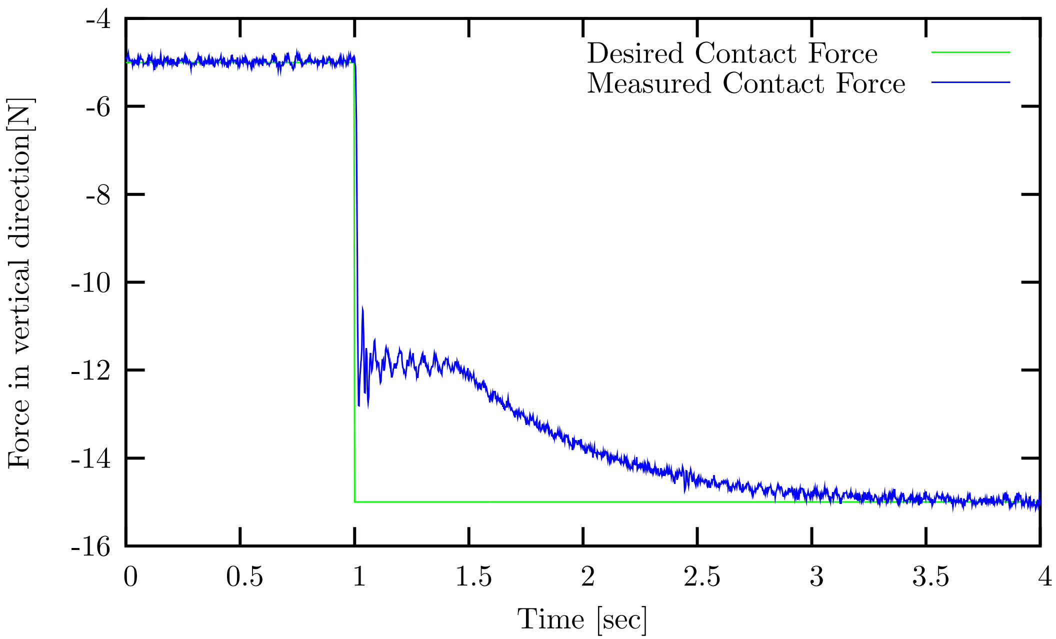


$$\begin{cases} \ddot{x}_m = f_m^* \\ \frac{1}{k_s}\ddot{f}_c = f_f^* \end{cases}$$

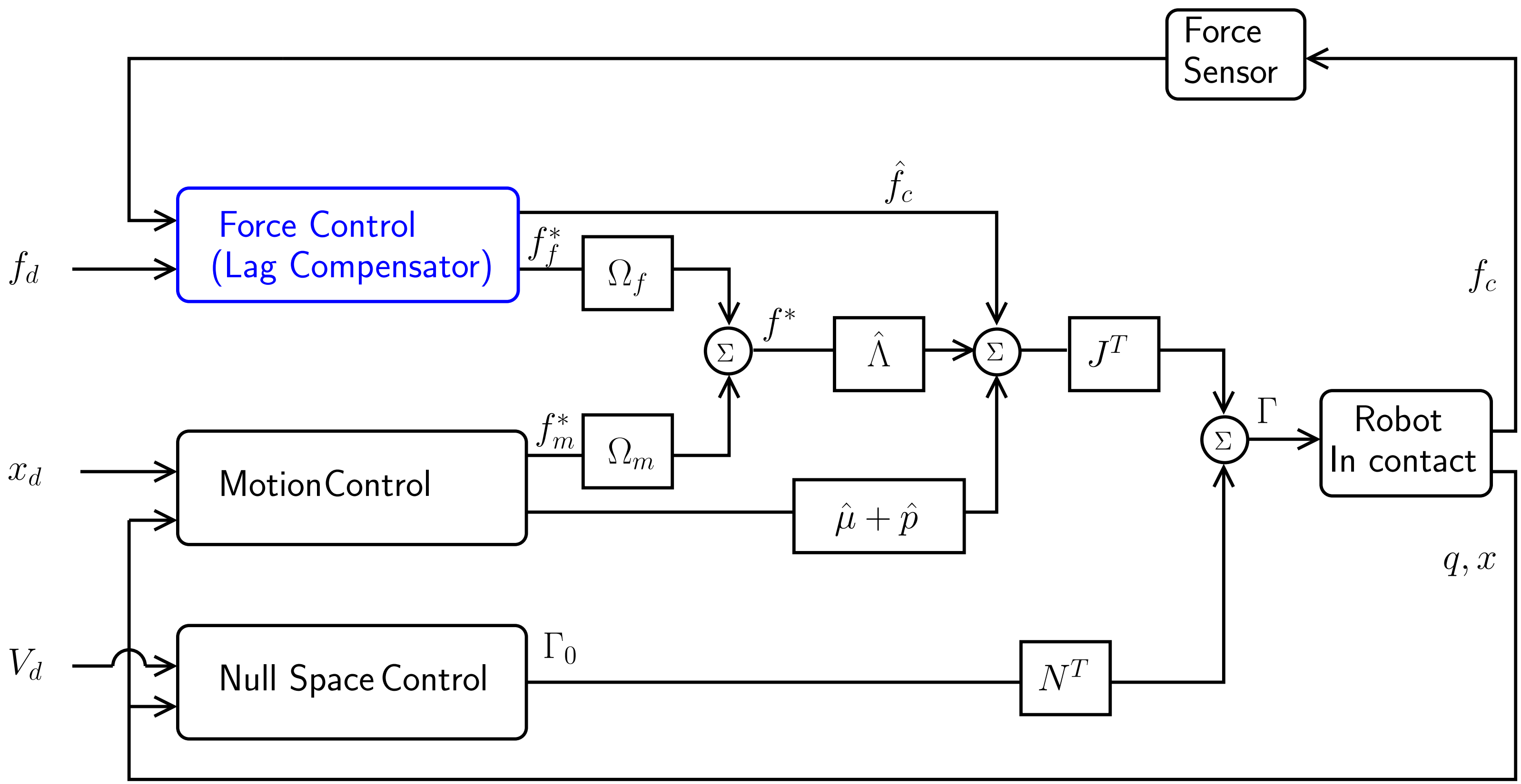
Force Control Result

One point contact with hard surface



Lag compensator

Motion/Force Control Framework



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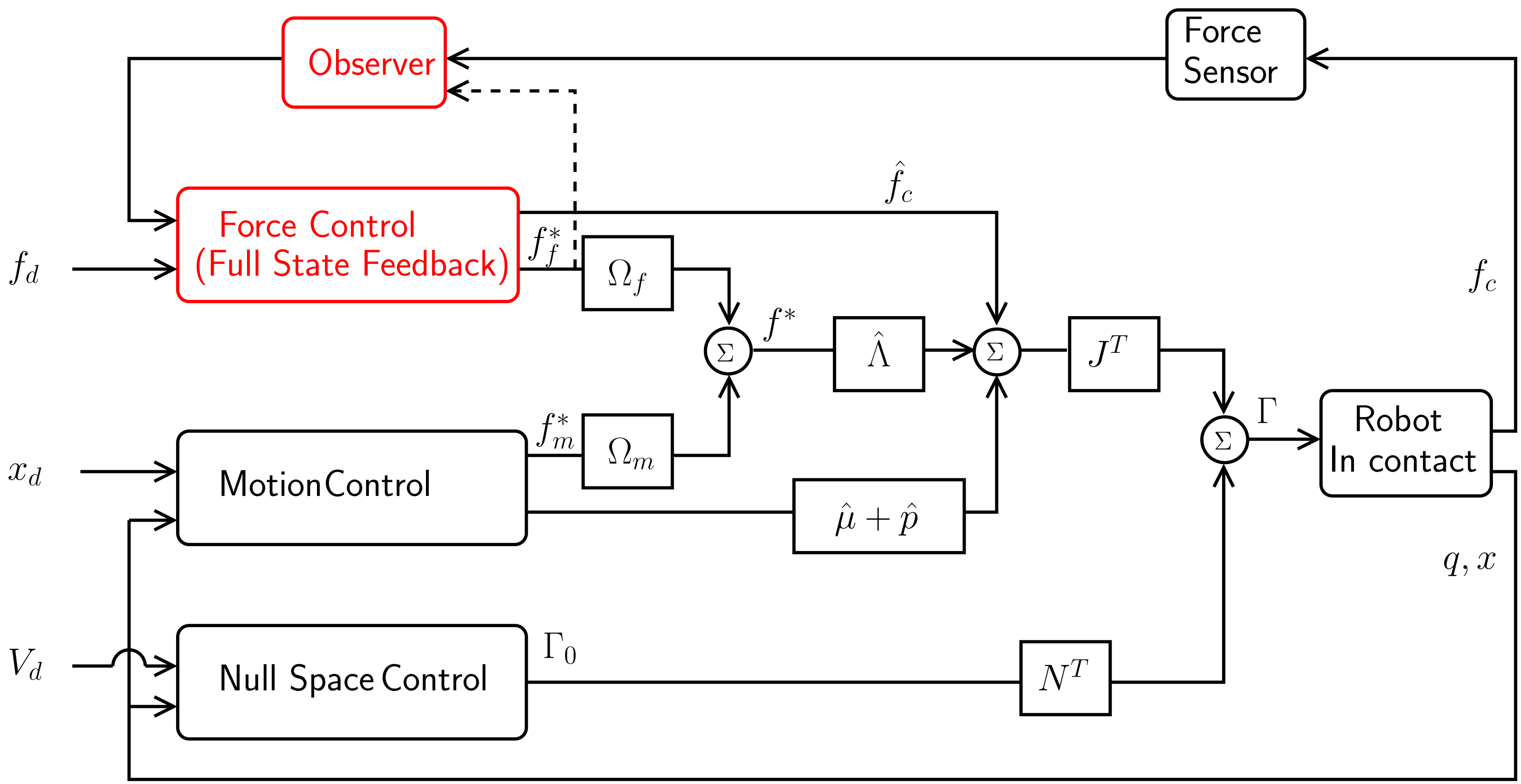

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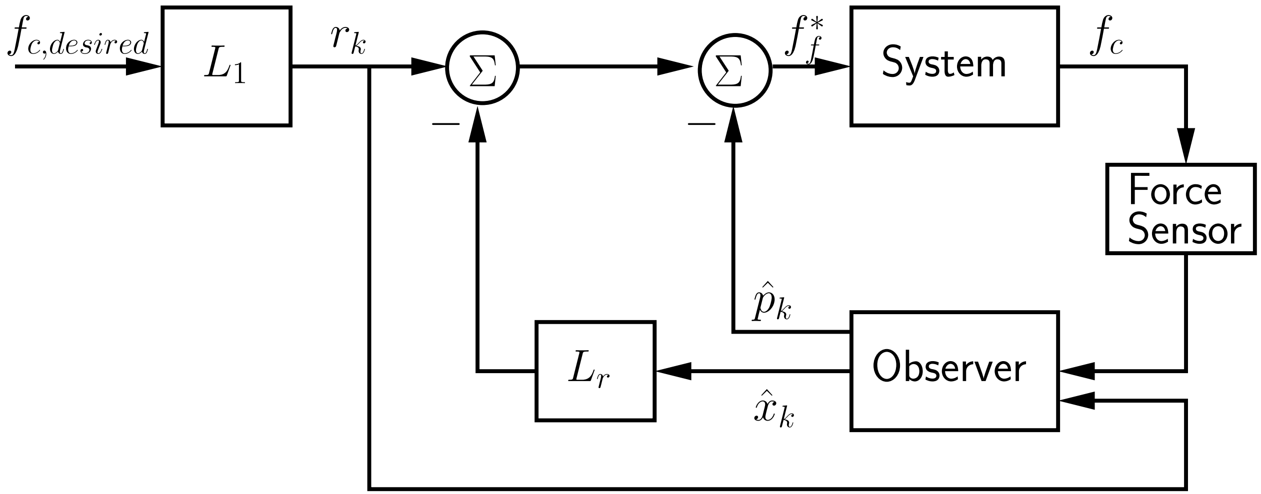
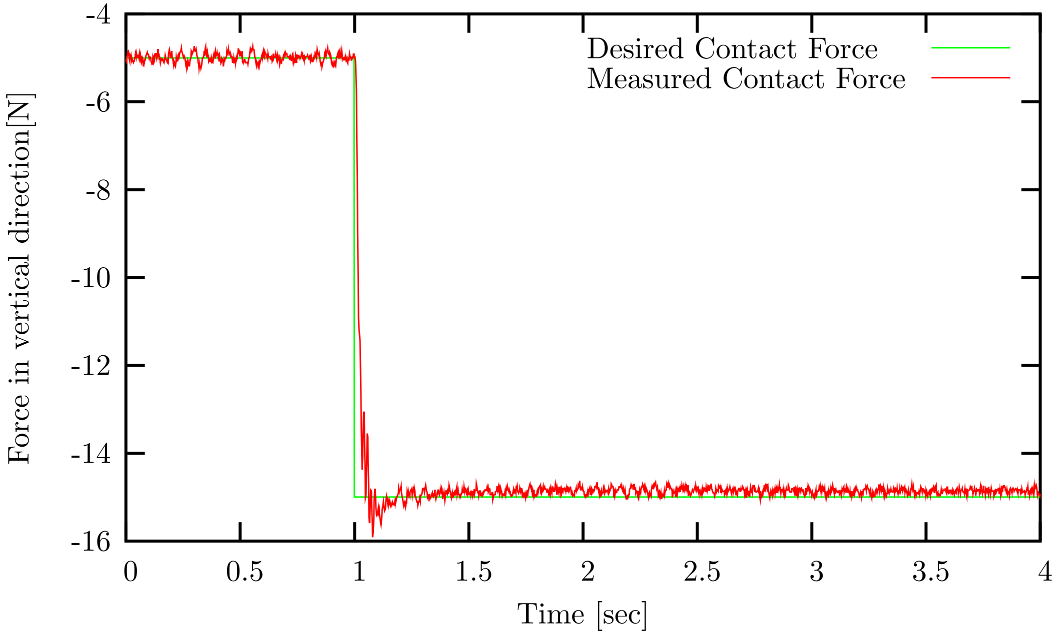
Control with Estimator

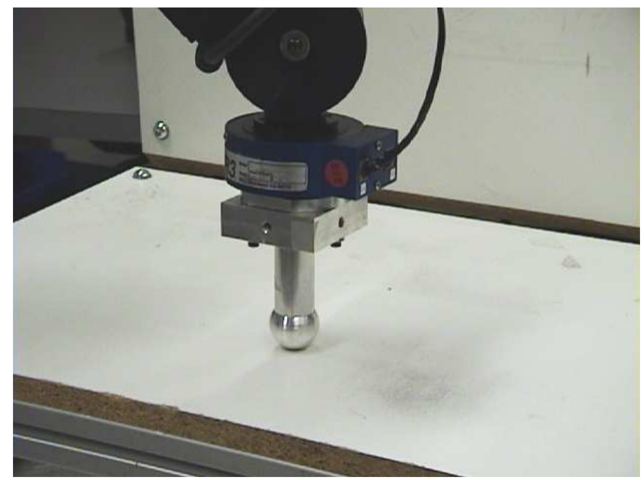


$\hat{x}_k$	state estimate - $\hat{f}_c$ and $\hat{\dot{f}}_c$
$\hat{p}_k$	input disturbance estimate
L_r	a full state feedback gain obtained by Pole Placement Method
L_1	a scaling factor to compute reference input
f_c	contact force
$f_{c,d}$	desired contact force
r_k	reference input

Force Control Result

One point contact with hard surface

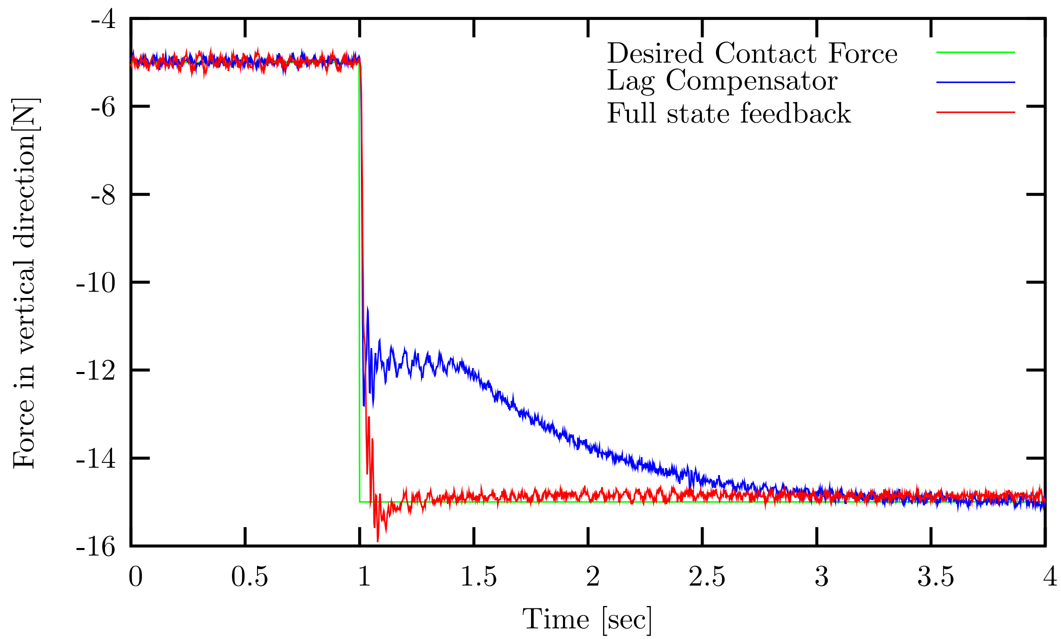




Full state feedback control

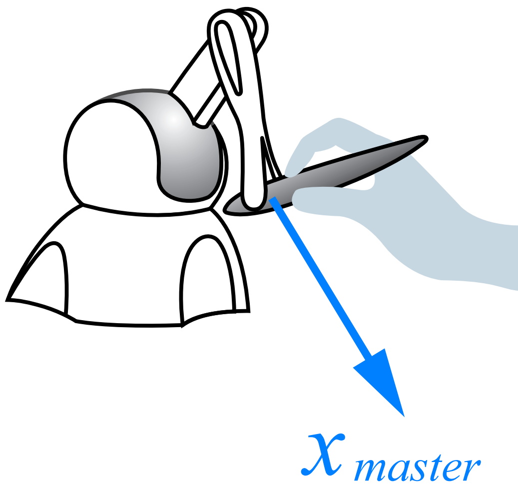
Force Control Result

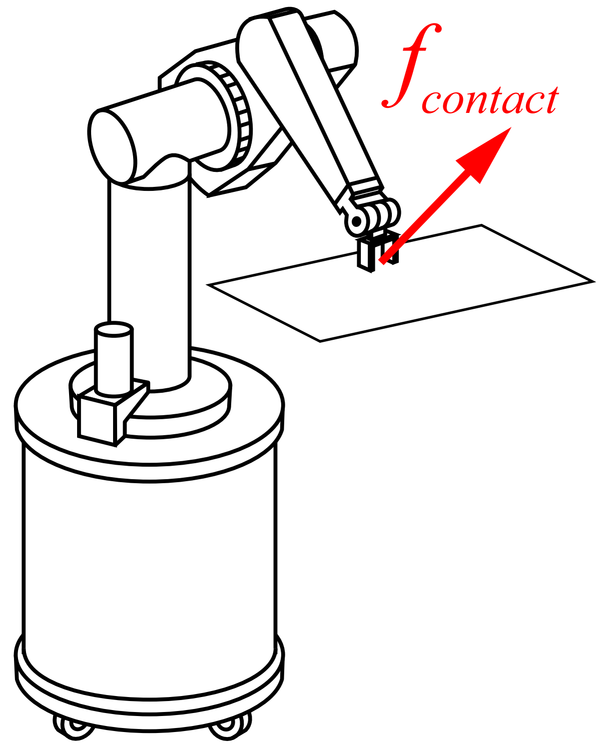
One point contact with hard surface



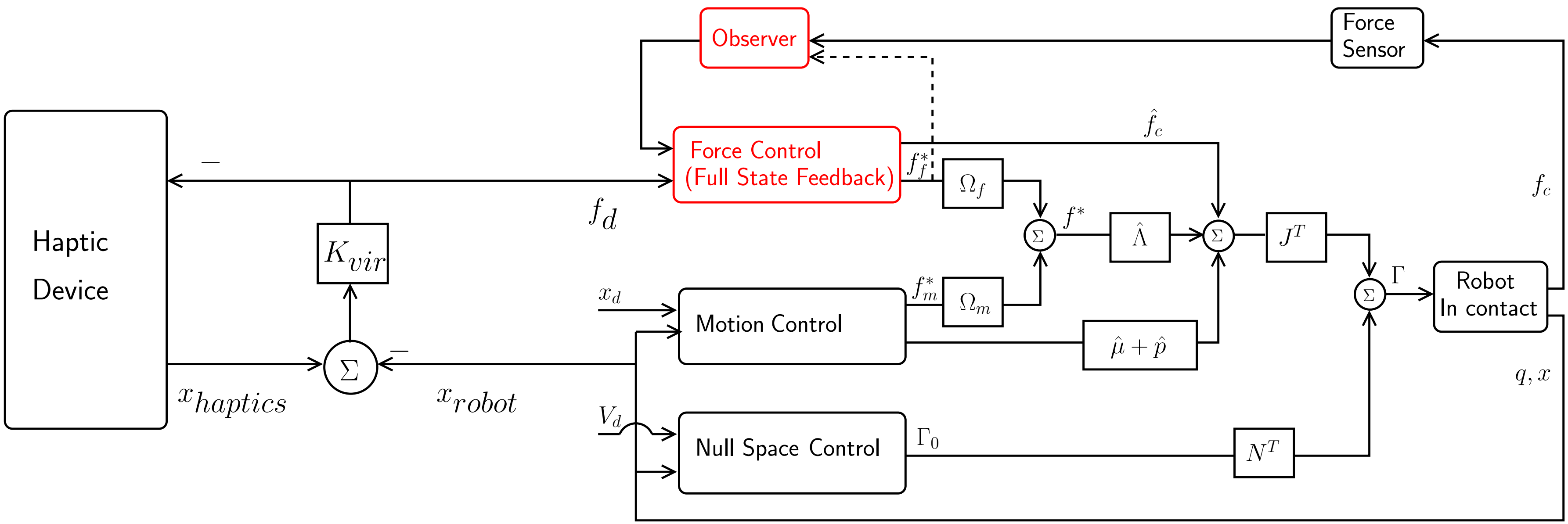
Comparison

Teleoperation





Teleoperation Scheme



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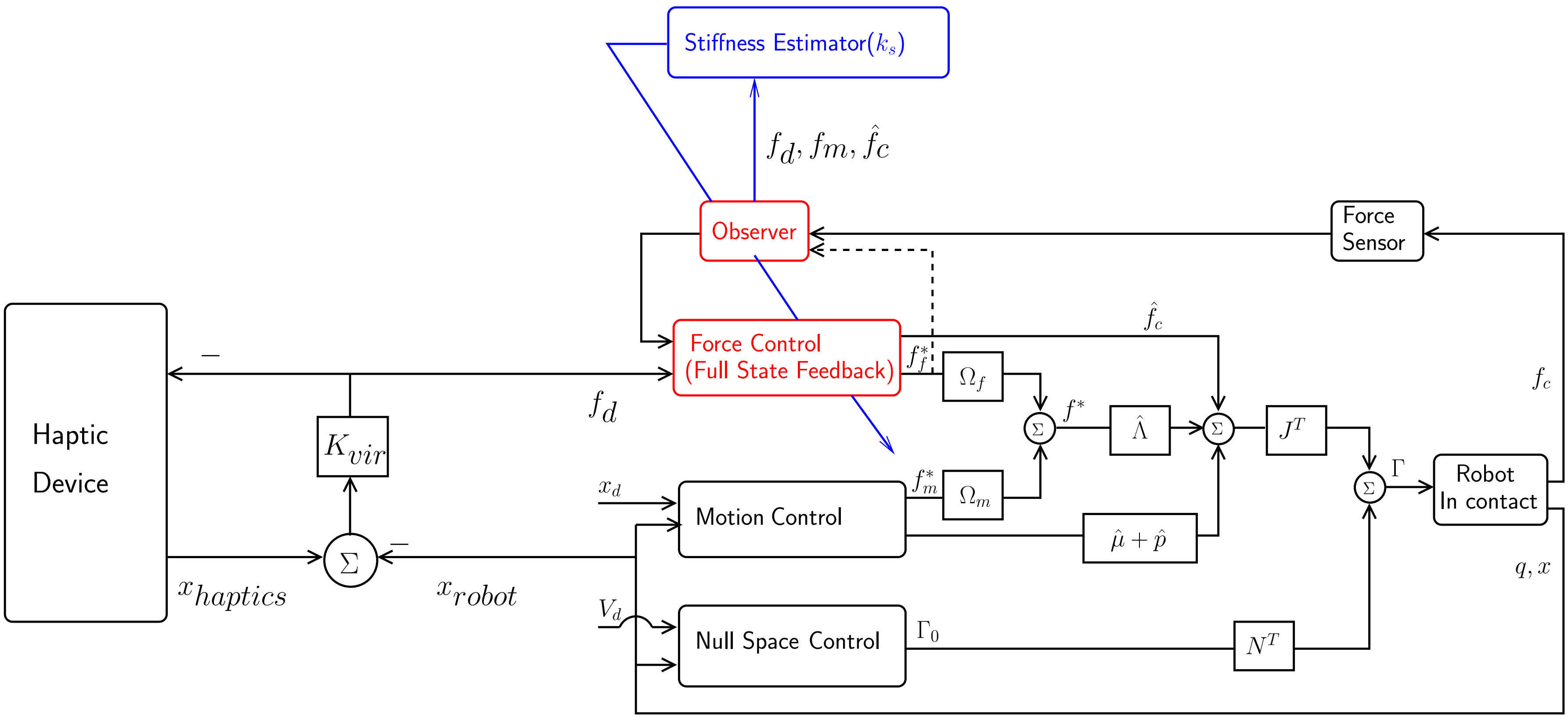


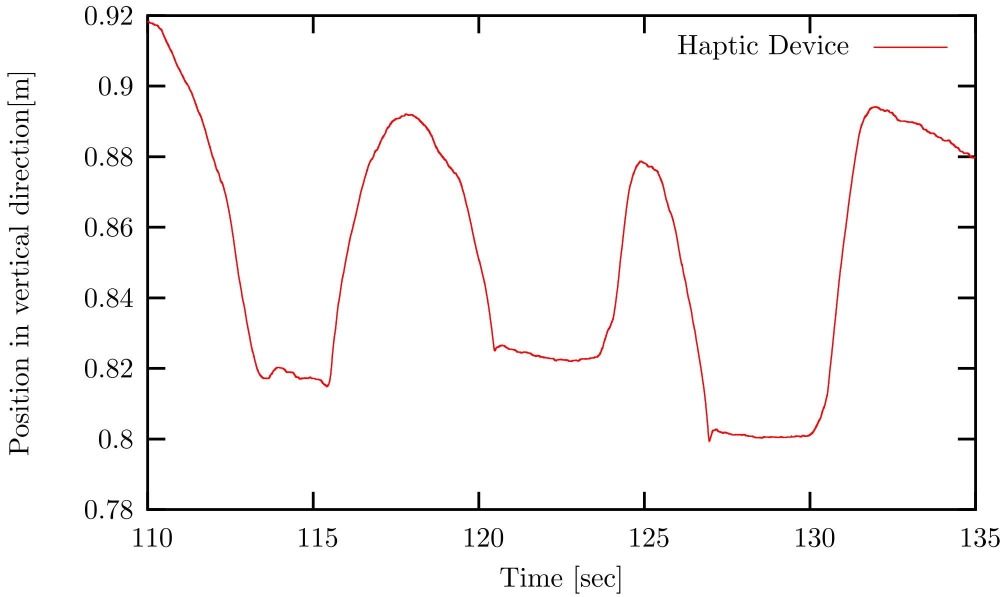
System Setup


- Master Haptic Device: PHANTOM 1.0 SensAble
- Stanford Mobile Platform: PUMA560 on XR4000

Experimental Results

- End-effector controlled by teleoperation
- Base motion is controlled in the null-space

Motion/Force Tracking



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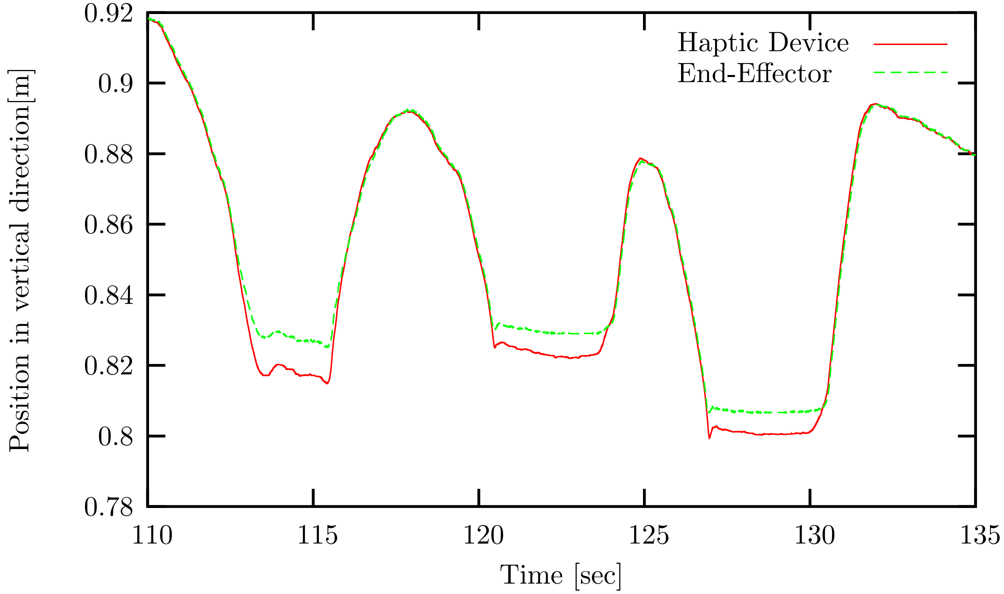

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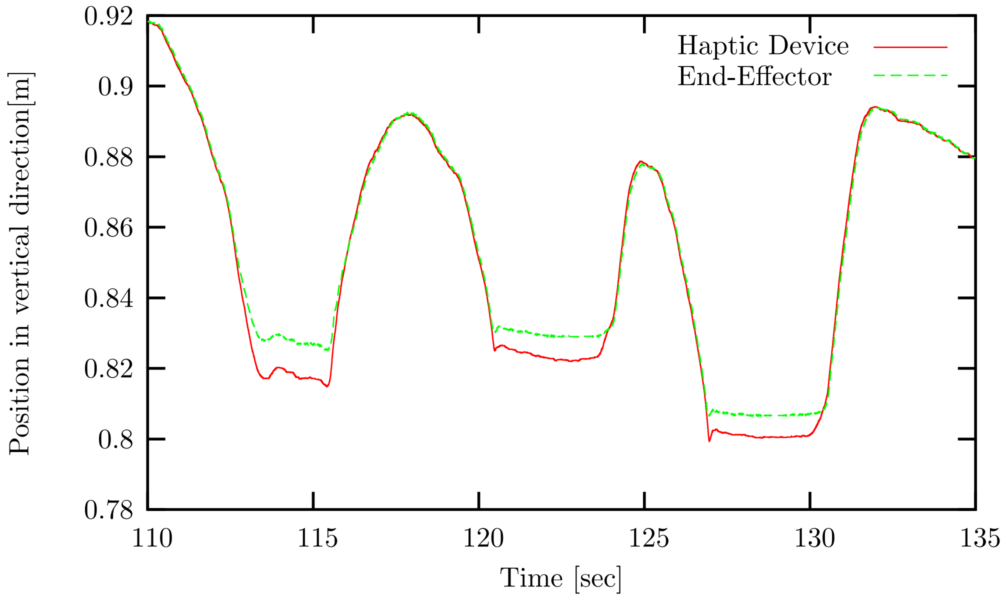

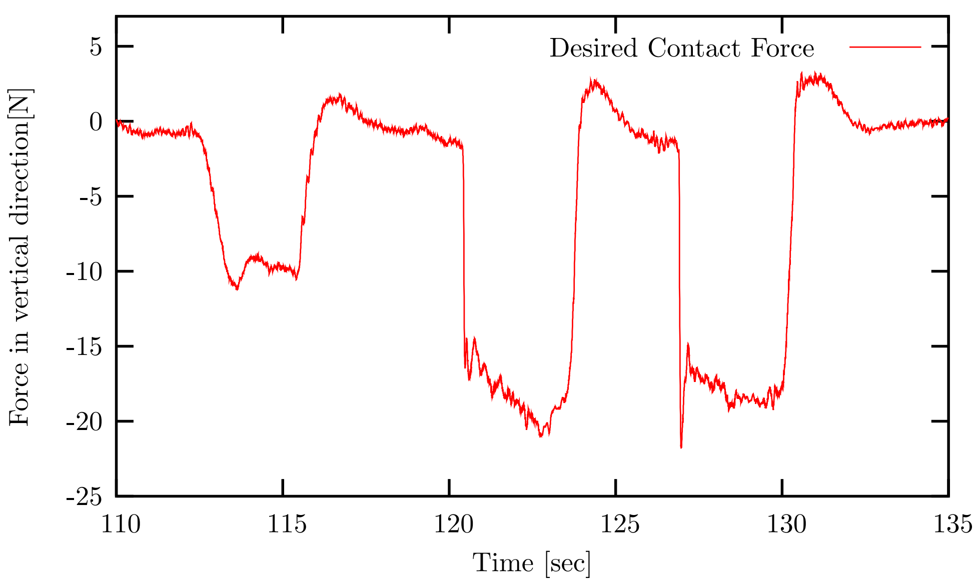

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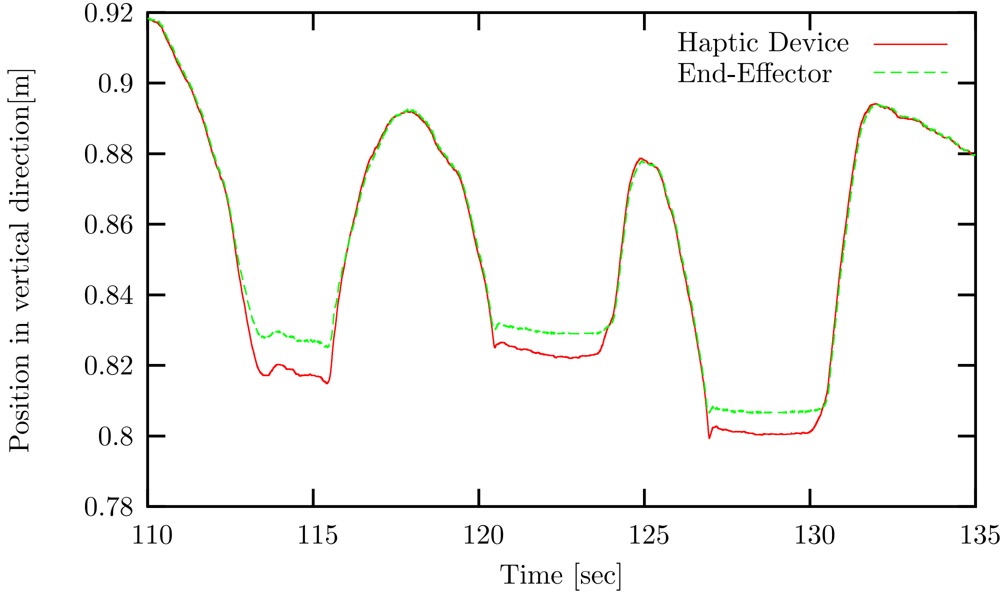

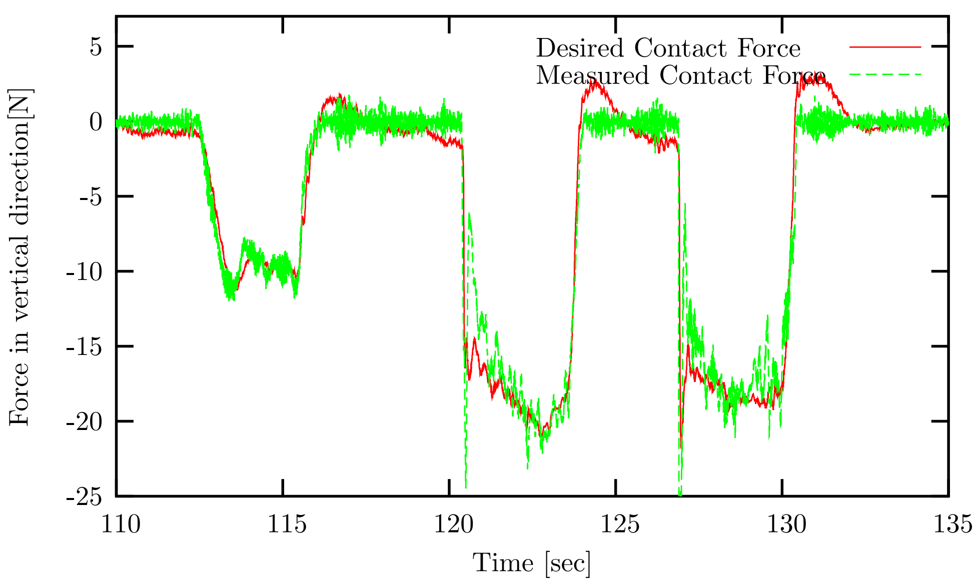

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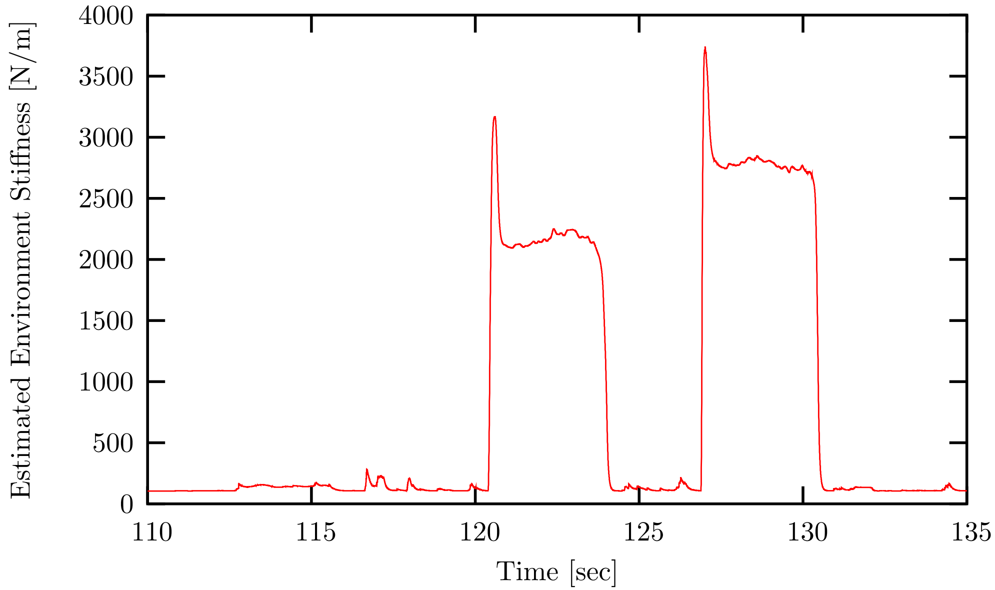
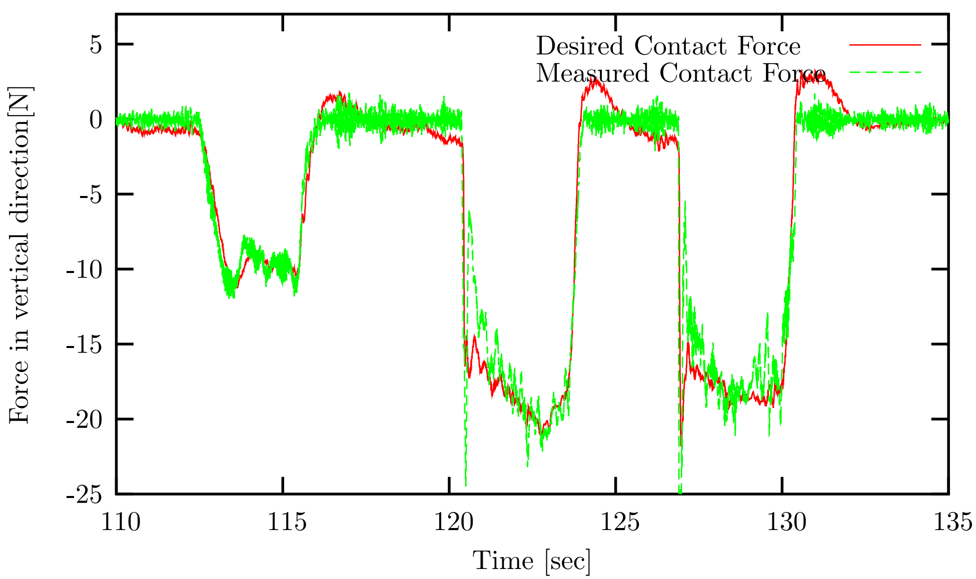
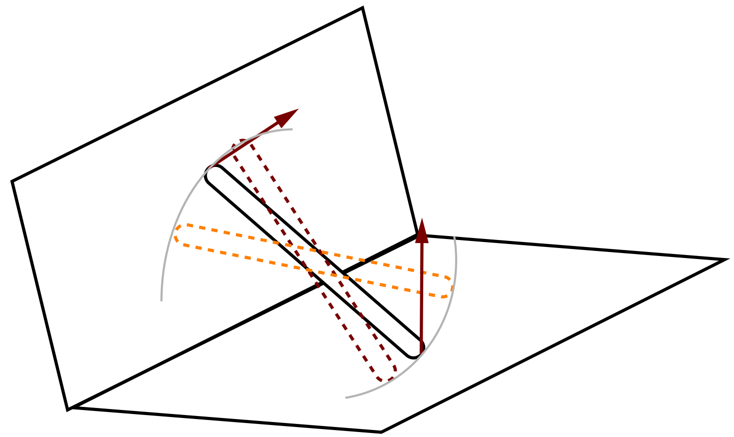




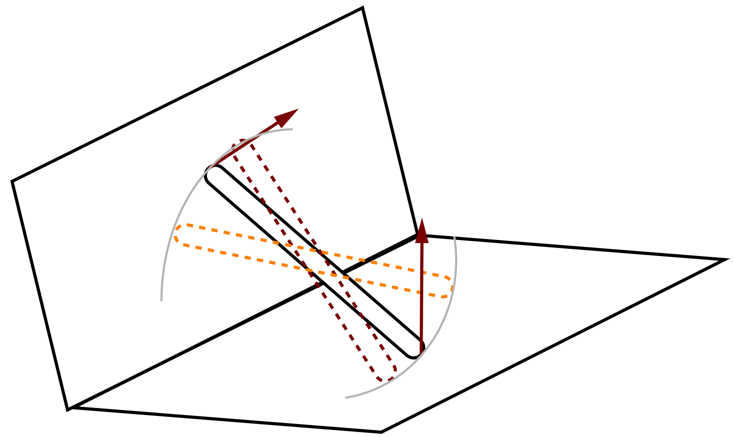
Juliet Setting a Dinner Table

Multiple Contacts



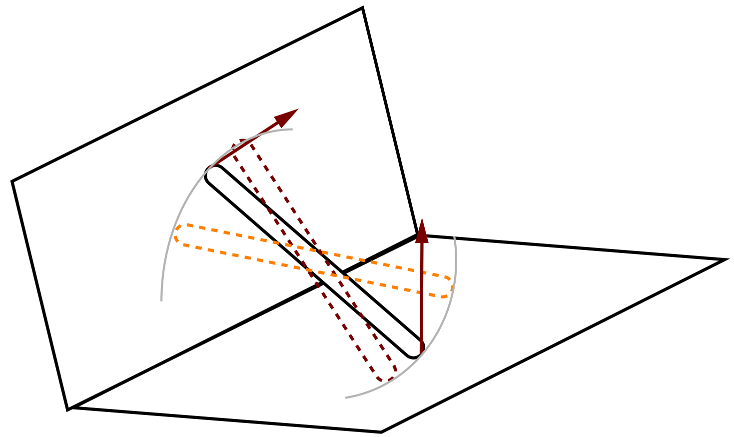
- Compliant frame selection matrices is not general enough to describe multi-contact

Multiple Contacts



- Compliant frame selection matrices is not general enough to describe multi-contact
- Special selection matrix $\Omega_f(n)$ and $\Omega_m(n)$
  - Featherstone, Sonck, and Khatib (1997)

Multiple Contacts



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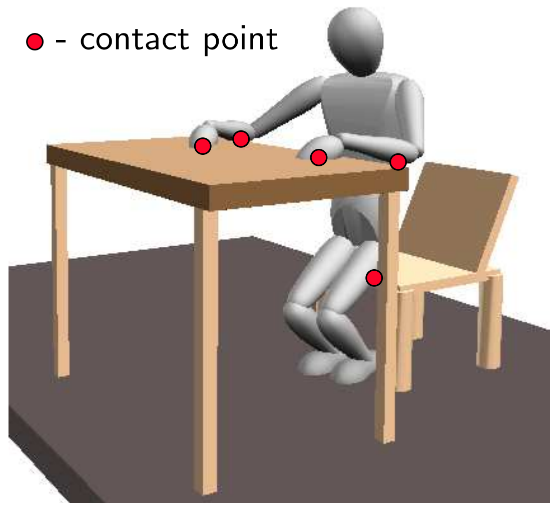
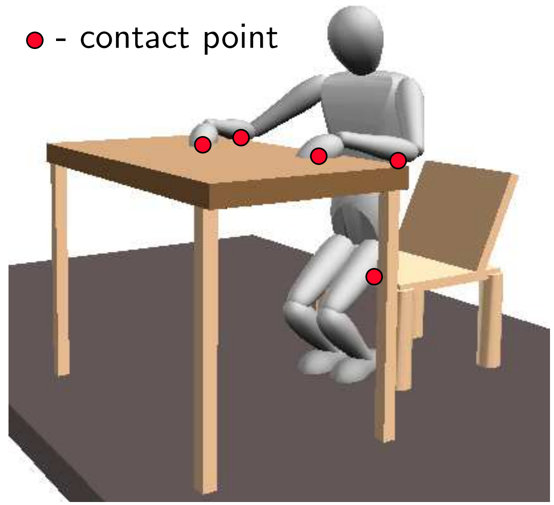
- Special selection matrix $\Omega_f(n)$ and $\Omega_m(n)$
  - Featherstone, Sonck, and Khatib (1997)
  - Bruyninckx and Schutter (1998)

Multi-link Multi-contact



$$\begin{pmatrix} \Lambda_{11} & \Lambda_{12} & \dots & \Lambda_{1m} \\ \Lambda_{21} & \Lambda_{22} & \dots & \Lambda_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ \Lambda_{m1} & \Lambda_{m2} & \dots & \Lambda_{mm} \end{pmatrix} \begin{pmatrix} \ddot{x}_1 \\ \ddot{x}_2 \\ \vdots \\ \ddot{x}_m \end{pmatrix} + \mu + p + f_c = \begin{pmatrix} F_1 \\ F_2 \\ \vdots \\ F_m \end{pmatrix}$$

Multi-link Multi-contact

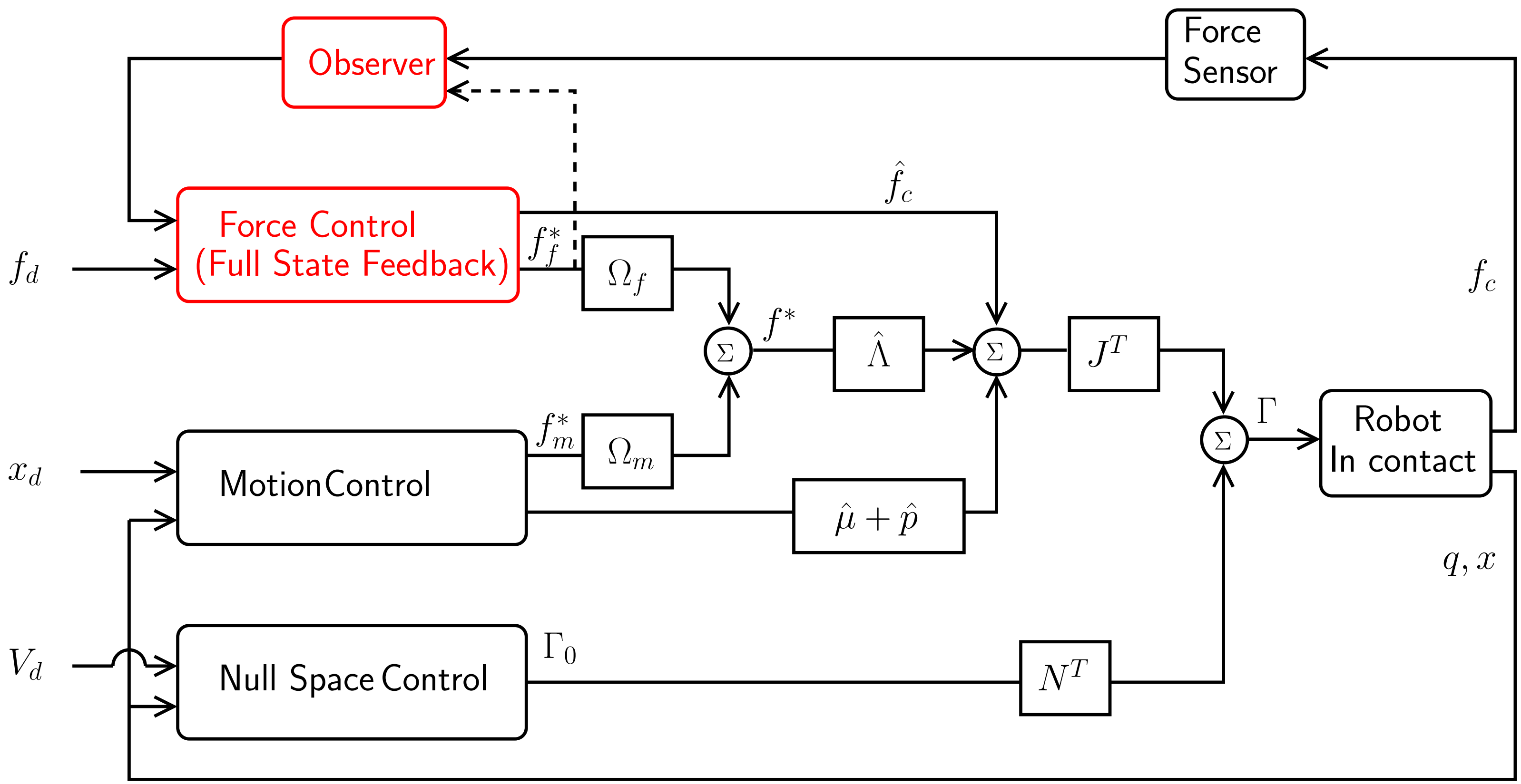


The spacial selection matrices will be defined by the contact normal directions of all the operational points : $\Omega_f(n_1, n_2, \ldots, n_l)$ and $\Omega_m(n_1, n_2, \ldots, n_l)$

$$F = \hat{\Lambda} f^* + \hat{\mu} + \hat{p} + \hat{f}_c$$

$$f^* = \Omega_f f_f^* + \Omega_m f_m^*$$

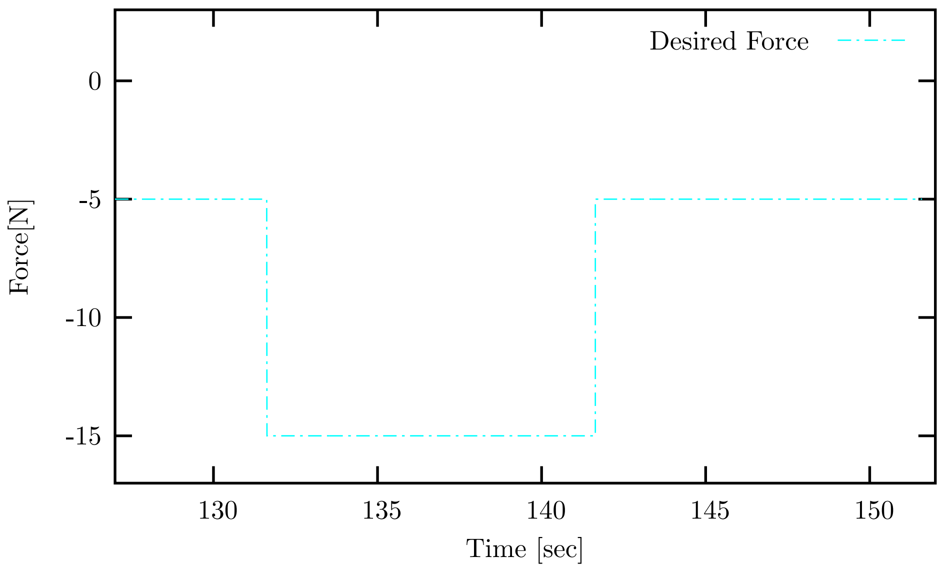
Motion/Force Control Framework

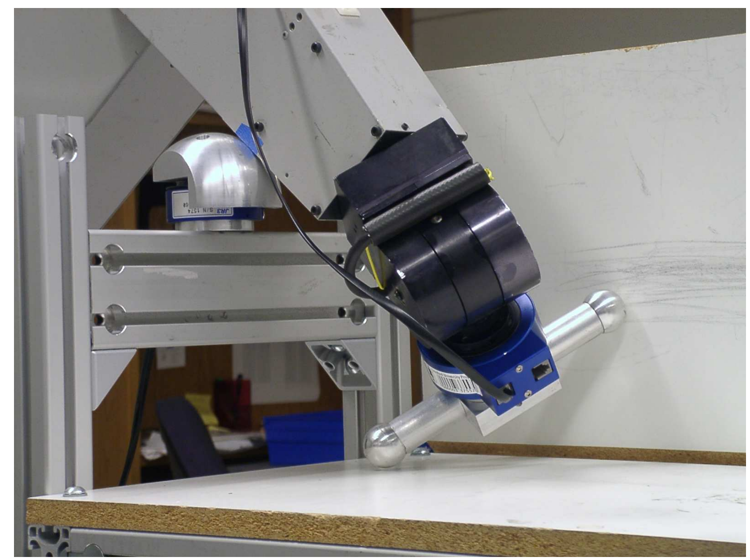


$$\begin{cases} \ddot{x}_m = f_m^* \\ \frac{1}{k_s}\ddot{f}_c = f_f^* \end{cases}$$

Three contact experiment

Two contact at the end-effector and one contact at the third link





Contact force measurement

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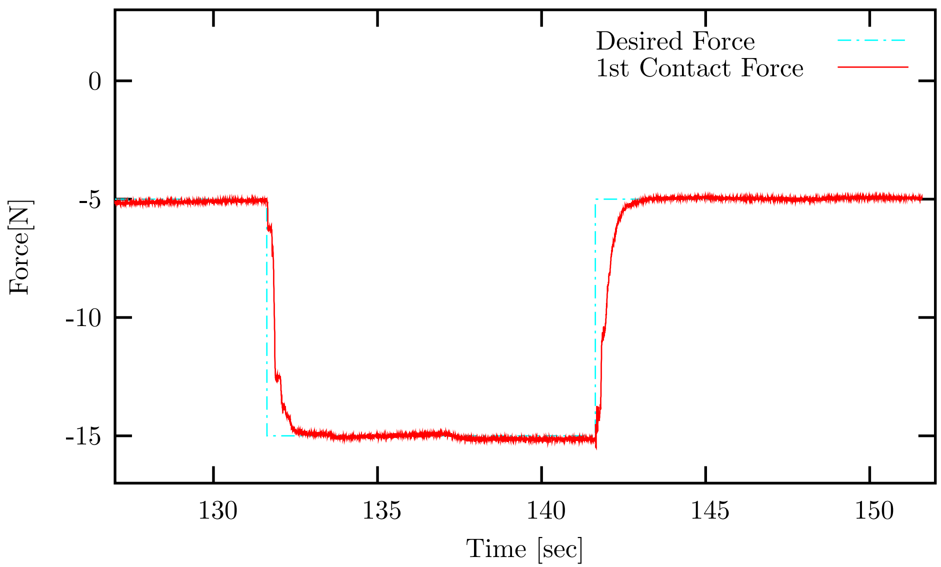

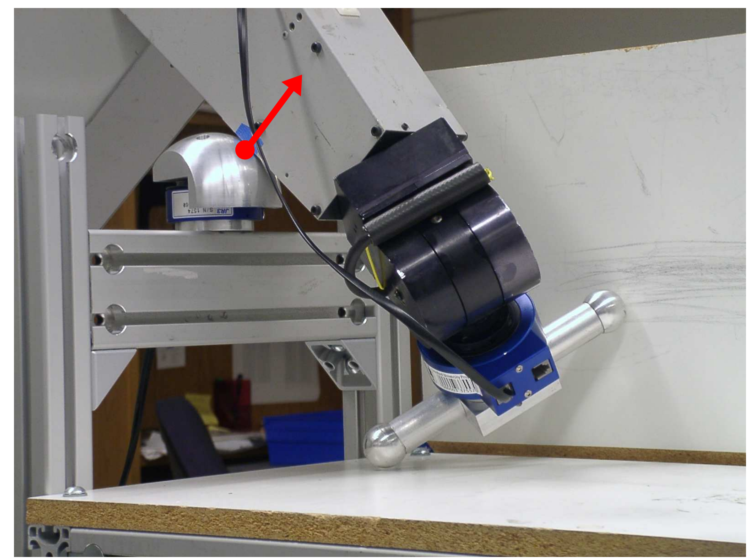

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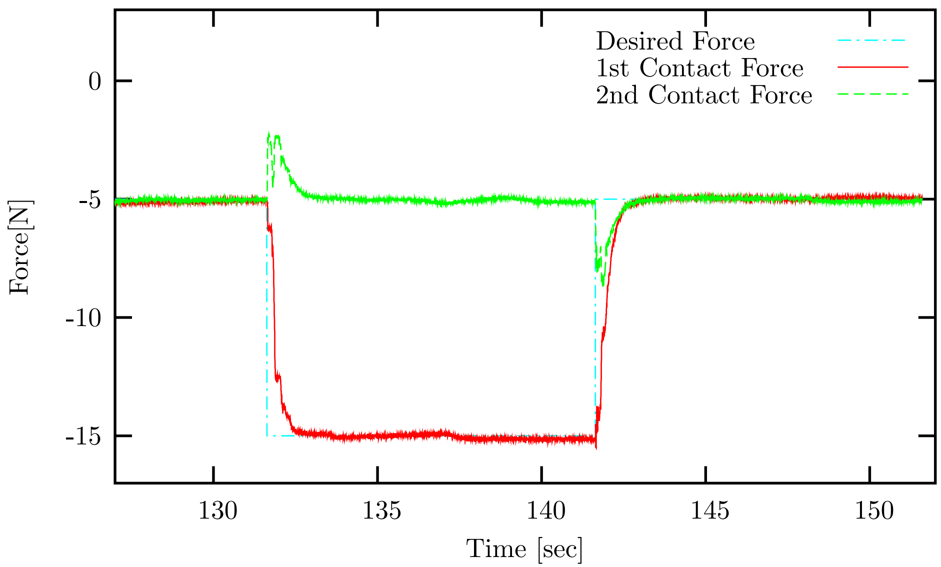

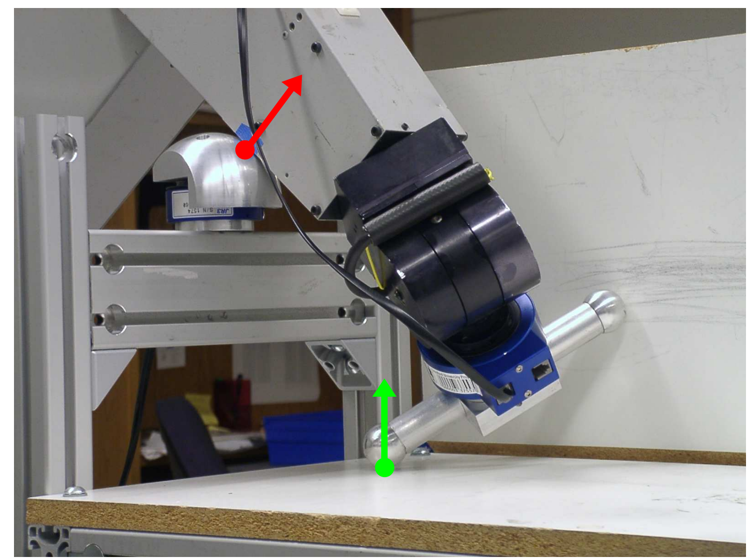

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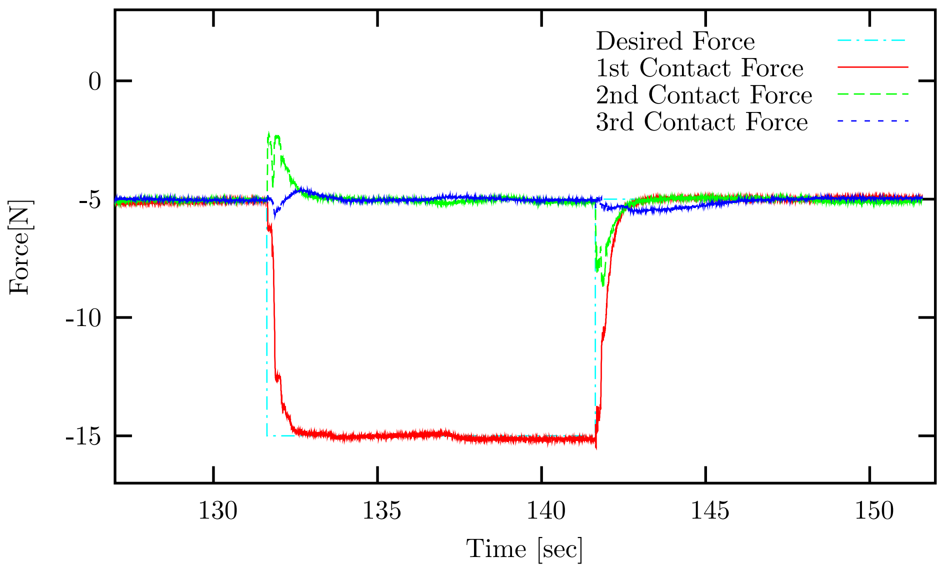
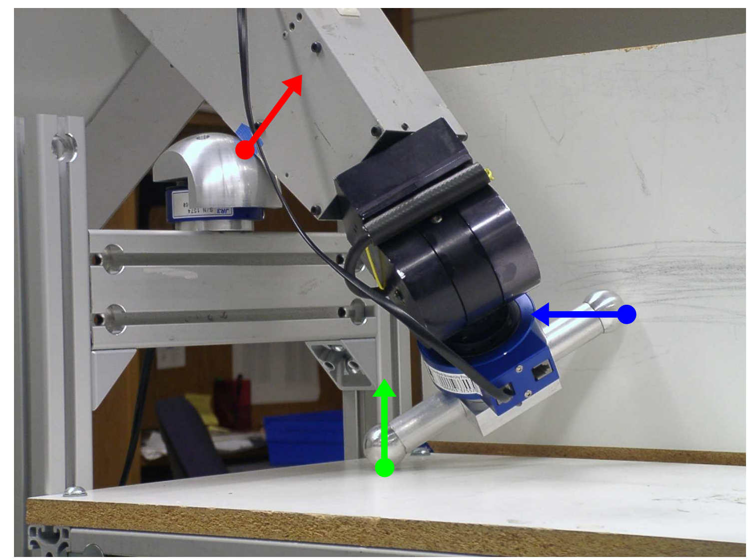
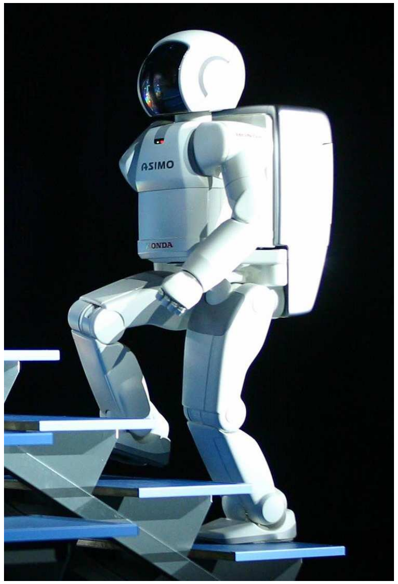




Contact force measurement

Three contact experiment with motion

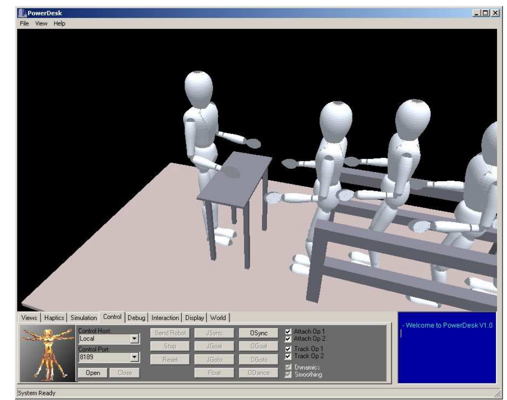
Humanoid robot



- Many humanoid systems have been built.
  Honda ASIMO, Sony SDR, HRP, and KHR
- Controls are still limited
  - mostly focused on walking
  - walking and manipulation are treated as separate problems

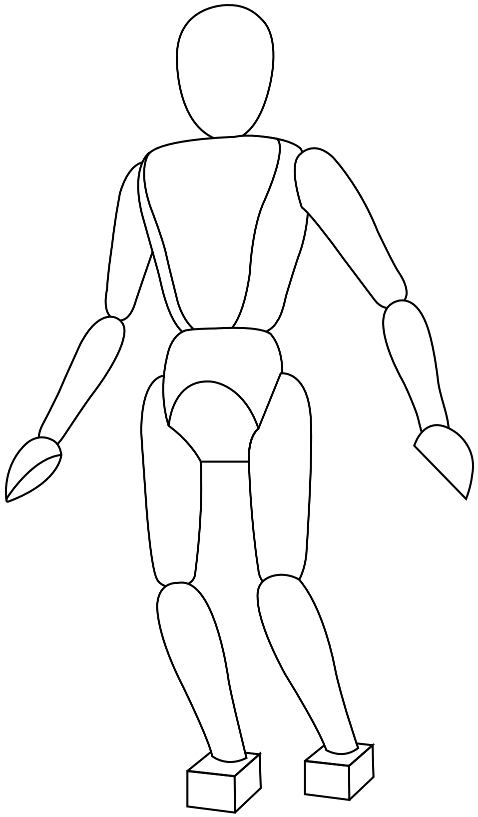
Humanoid Research in the group

- Whole-body control framework
  - Whole-body dynamic behavior and control of human-like robots
    (Khatib, Sentis, Park, Warren 2004)
- SAI simulation environment
  - Dynamic simulation
    -Efficient recursive algorithm for the operational space inertia matrix of branching mechanisms (Chang, Khatib 2001)
    -A framework for multi-contact multi-body dynamic simulation and Haptic Display (Ruspini, Khatib 2000)



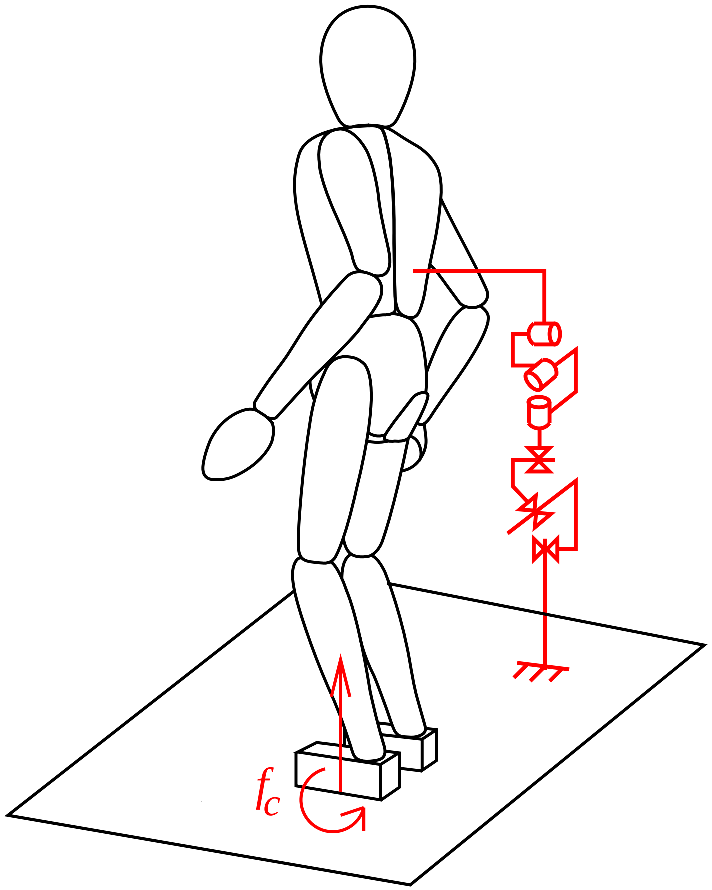
  - SAI graphics engine and programming environment - Conti, Pashchenko
- Learning from human motion
  - Simulating the Task-level Control of Human Motion: A Methodology and Framework for Implementation
    (De Sapio, Warren, Khatib, and Delp 2005)
- Control implementation on ASIMO - Thaulad

Humanoid robot characteristics



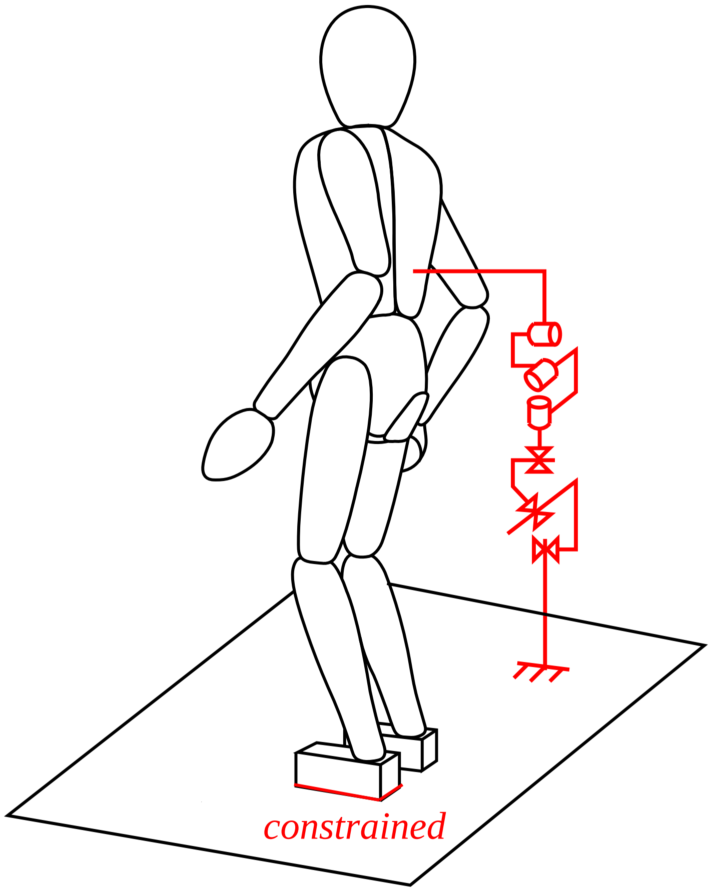
- Under-actuated system in free space
  - Non fixed base
- Contacts are necessary to support the system

Constrained dynamics of robot



$$A(q)\ddot{q} + b(q,\dot{q}) + g(q) + J_c^T f_c = \Gamma$$

Constrained dynamics of robot

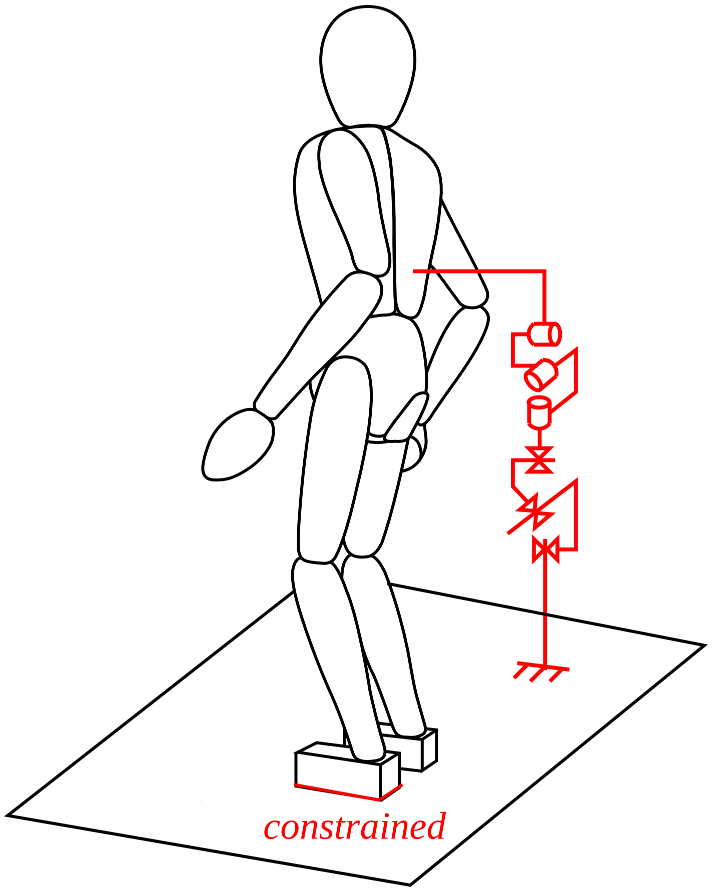


$$A(q)\ddot{q} + b(q,\dot{q}) + g(q) + J_c^T f_c = \Gamma$$

By treating the contacts as constraints, $\ddot{x}_c = 0$ and $\dot{x}_c = 0$,

$$f_c = \bar{J}_c^T(q)\Gamma - \mu_c(q,\dot{q}) - p_c(q)$$

Constrained dynamics of robot



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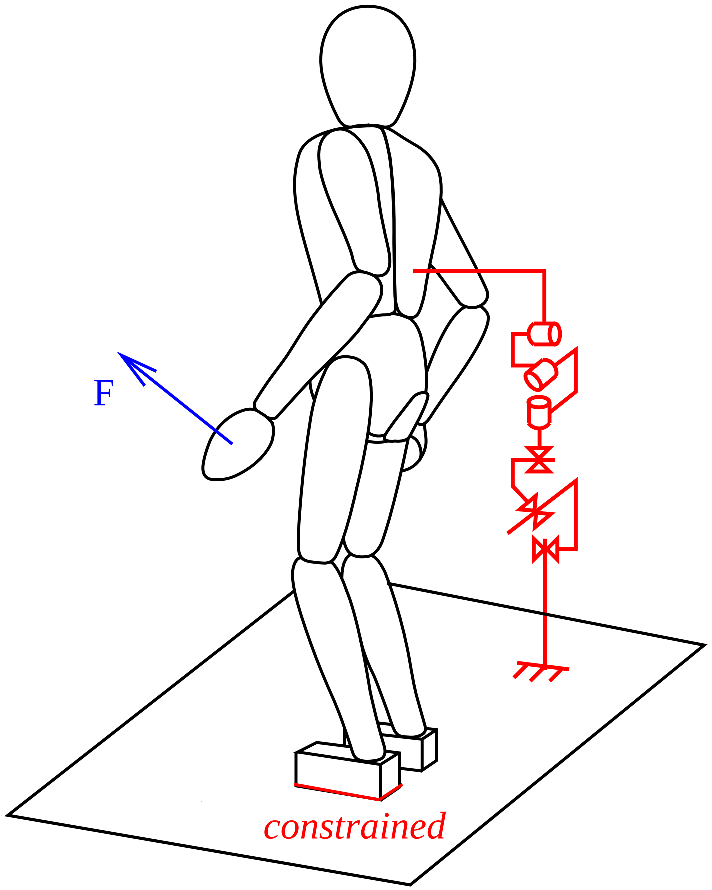
$$\begin{aligned} \Rightarrow A(q)\ddot{q} + b(q,\dot{q}) + g(q) & \\ - J_c^T(\mu_c(q,\dot{q}) + p_c(q)) & \\ = (I - J_c^T \bar{J}_c^T)\Gamma & \end{aligned}$$

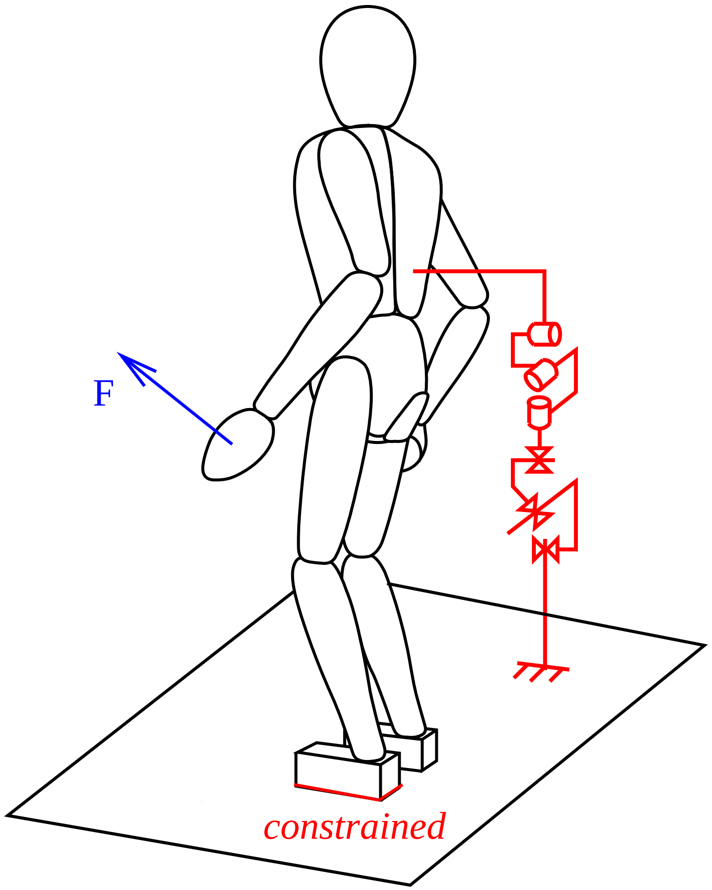
Operational Space Dynamics



Constrained Joint Space Dynamics

$$A\ddot{q} + b + g - J_c^T(\mu_c + p_c)$$
$$= (I - J_c^T \bar{J}_c^T)\Gamma$$

Operational Space Dynamics



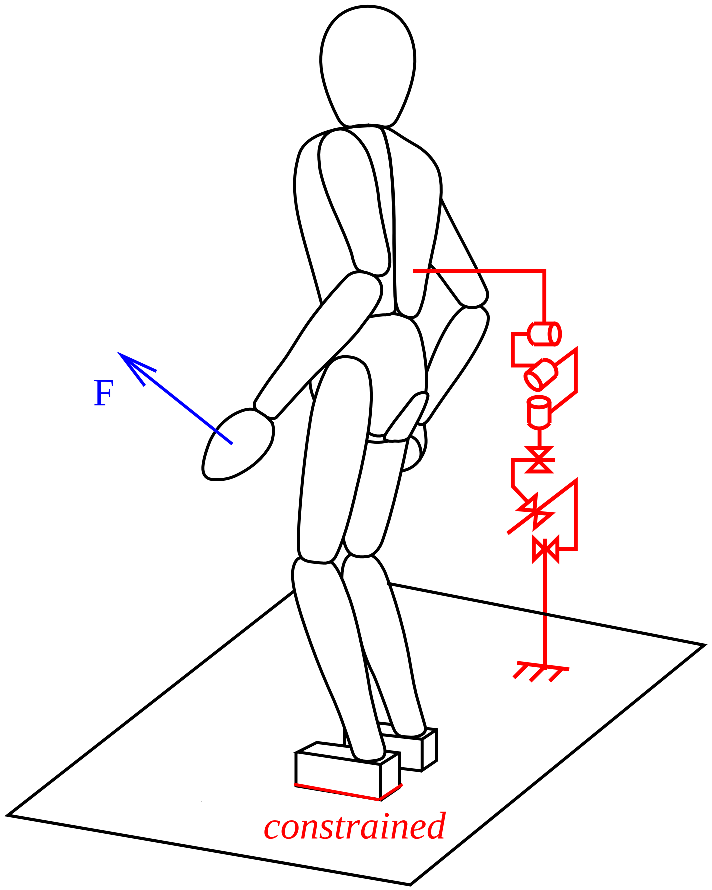
Constrained Joint Space Dynamics

$$A\ddot{q} + b + g - J_c^T(\mu_c + p_c) = (I - J_c^T \bar{J}_c^T)\Gamma$$

Constrained Operational space dynamics

$$\Lambda \ddot{x} + \mu(q, \dot{q}) + p(q) = F$$

Operational Space Dynamics



Constrained Joint Space Dynamics

$$A\ddot{q} + b + g - J_c^T(\mu_c + p_c)$$
$$= (I - J_c^T \bar{J}_c^T)\Gamma$$

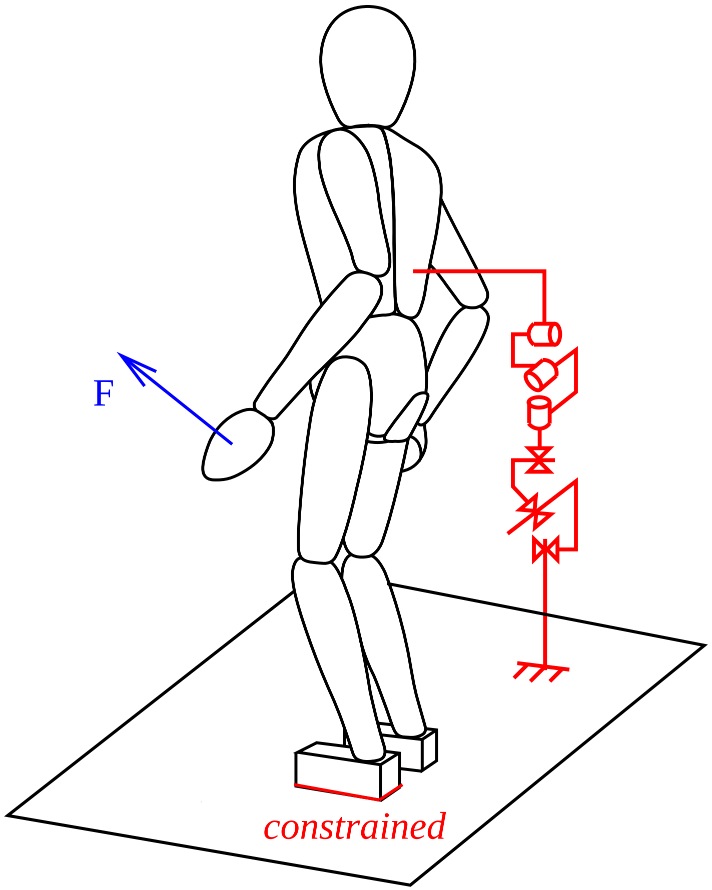
Constrained Operational space dynamics

$$\Lambda\ddot{x} + \mu(q,\dot{q}) + p(q) = F$$

Control Force

$$F = \hat{\Lambda} f^* + \hat{\mu} + \hat{p}$$

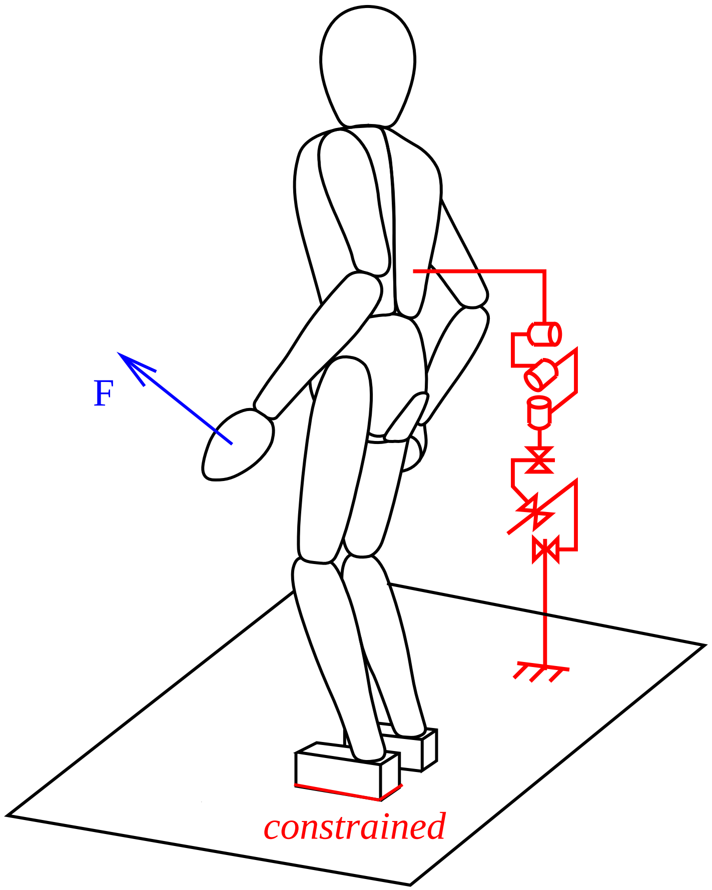
Control Torque



The relation between joint torque and force

$$\Gamma = J^T F$$

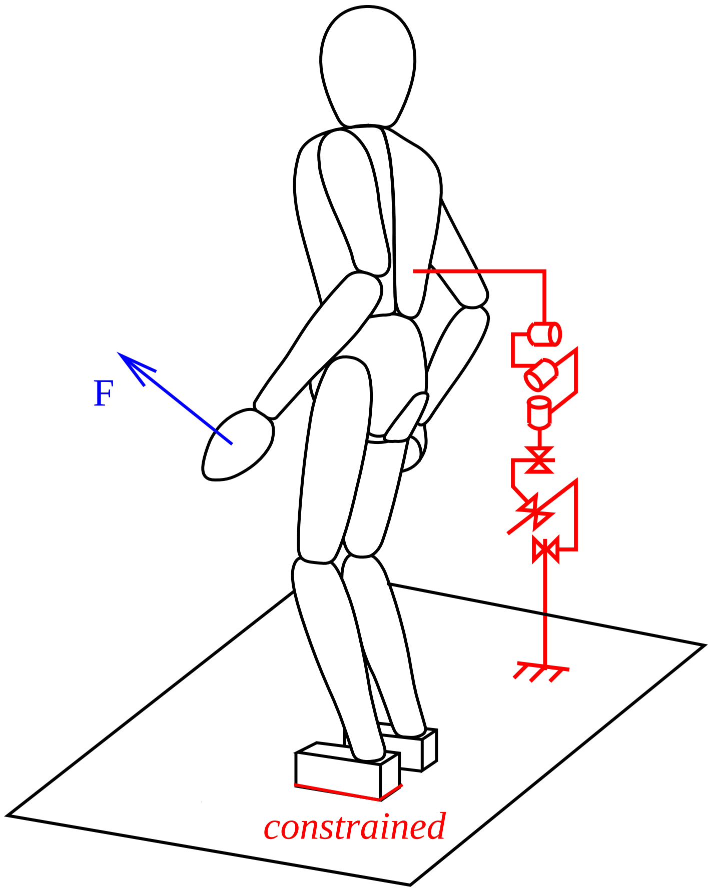
Control Torque



The relation between joint torque and force

$$F = \bar{J}^T \Gamma$$

Control Torque



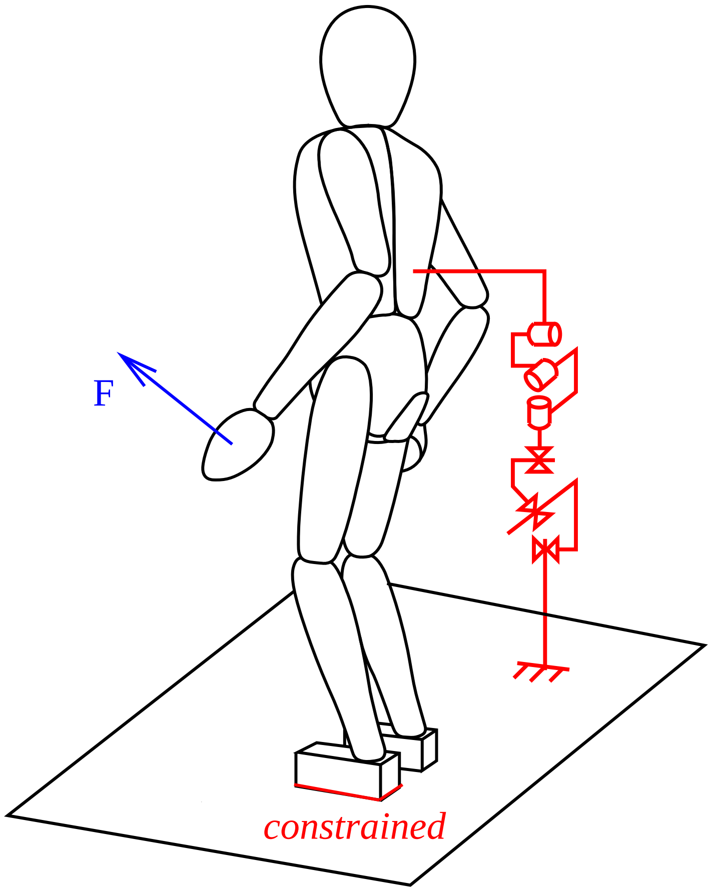
The relation between joint torque and force

$$F = \bar{J}^T \Gamma$$

Torques at virtual joints are zero.

$$F = \bar{J}^T S^T \Gamma_{actuated}$$

Control Torque



The relation between joint torque and force

$$F = \bar{J}^T \Gamma$$

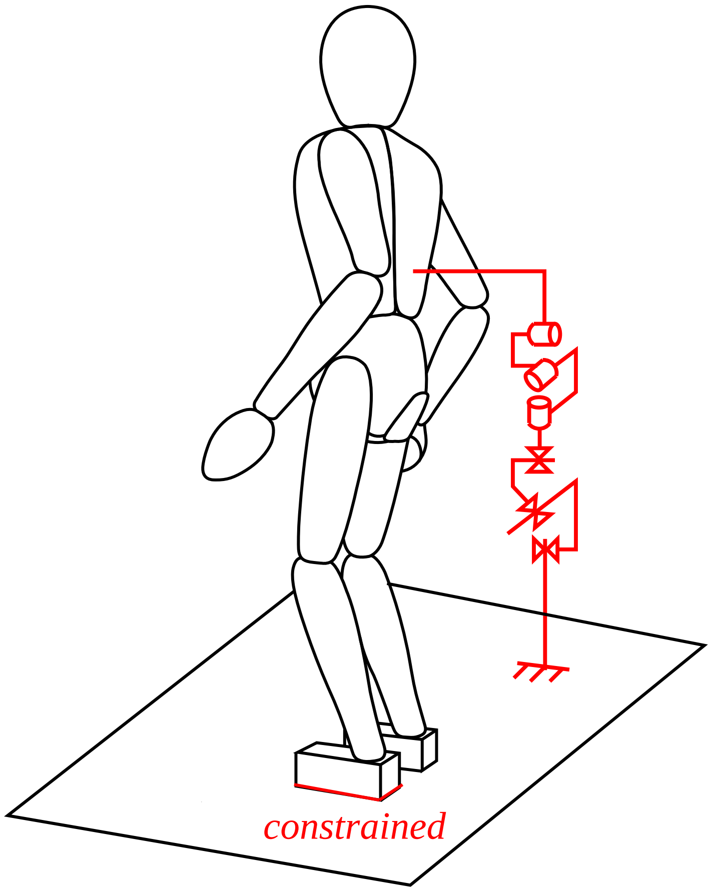
Torques at virtual joints are zero.

$$F = \bar{J}^T S^T \Gamma_{actuated}$$

The Control torque is

$$(\Gamma_{actuated})_{task} = \overline{\bar{J}^T S^T} F$$

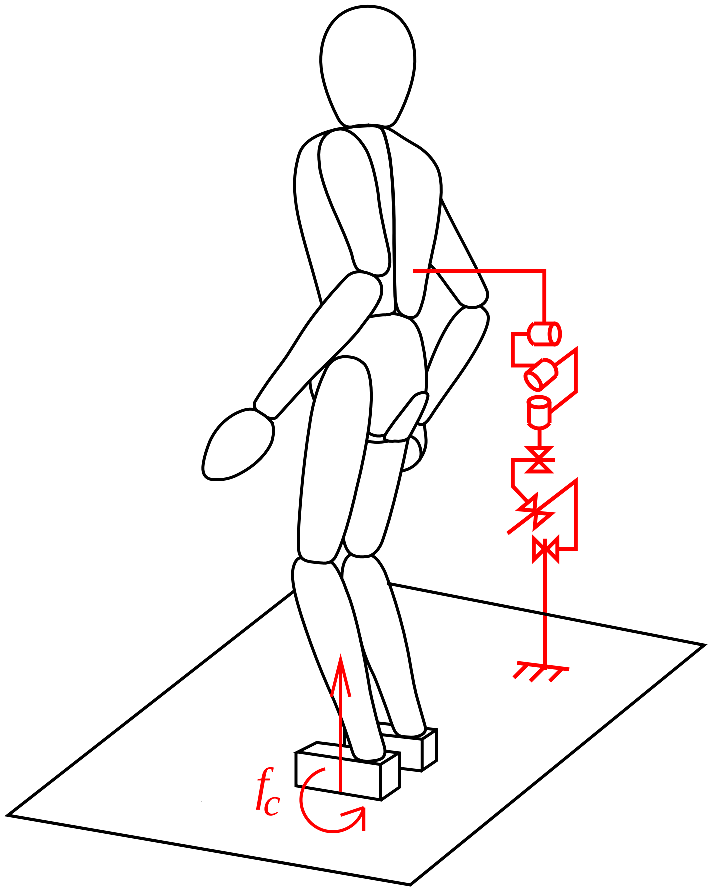
Constrained dynamics of robot



$$A\ddot{q} + b + g - J_c^T(\mu_c + p_c)$$
$$= (I - J_c^T \bar{J}_c^T)\Gamma$$

$$f_c = \bar{J}_c^T \Gamma - \mu_c(q, \dot{q}) - p_c(q)$$

Constrained dynamics of robot



$$A\ddot{q} + b + g - J_c^T(\mu_c + p_c)$$
$$= (I - J_c^T \bar{J}_c^T)\Gamma$$

$$f_c = \bar{J}_c^T \Gamma - \mu_c(q, \dot{q}) - p_c(q)$$

$$f_{c,i}|_{min} < f_{c,i} < f_{c,i}|_{max}$$

Reaction Force Control

$$\Gamma_{actuated} = (\Gamma_{actuated})_{task}$$

Reaction forces are given by

$$f_c = \bar{J}_c^T S^T (\Gamma_{actuated})_{task} - \mu_c(q, \dot{q}) - p_c(q)$$

Reaction Force Control

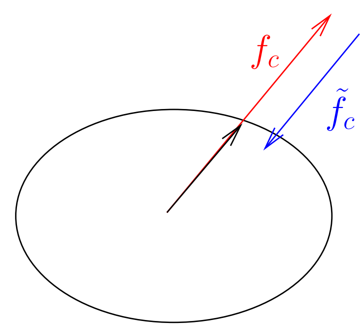
$$\Gamma_{actuated} = (\Gamma_{actuated})_{task} + (\Gamma_{actuated})_{contact}$$

Reaction forces are given by

$$f_c = \bar{J}_c^T S^T (\Gamma_{actuated})_{task} - \mu_c(q, \dot{q}) - p_c(q)$$

Modify control torque if they exceed the boundaries,

$$(\Gamma_{actuated})_{contact} = \overline{\bar{J}_c^T S^T} \tilde{f}_c$$



Standing on two feet

Gravity compensation with reaction force control

Balancing

Controlled operational space coordinates

- Position of Center of Mass AND Orientation of head, chest, and hip

Walking

Controlled operational space coordinates

- Position of Center of Mass AND Orientation of head, chest, and hip
- Left or right foot in one foot supporting

Jumping

Controlled operational space coordinates

- Position of Center of Mass AND Orientation of head, chest, and hip
- Both feet at no contact

Climbing Ladder

Controlled operational space coordinates

- Position of Center of Mass AND Orientation of head, chest, and hip
- Hands or feet in climbing

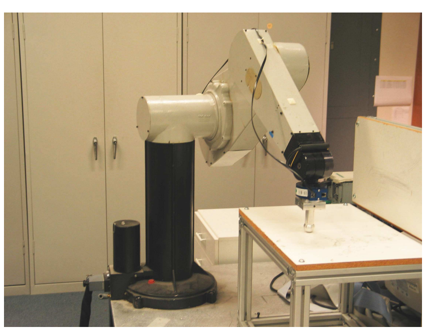
Manipulation combined with walking

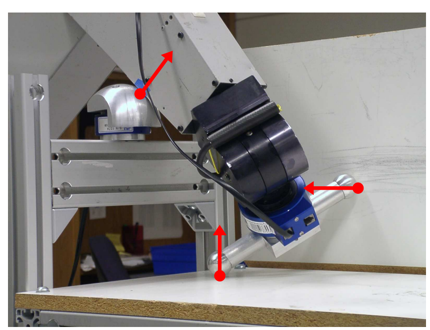
Controlled operational space coordinates

- Position of Center of Mass AND Orientation of head, chest, and hip
- Position and Force control of right hand

Conclusion

- Robust force control was developed for multi-body robotic systems.
  - High performance was demonstrated using full state feedback with Kalman estimator (improvement over lag compensator).
- Haptic teleoperation was implemented.
  - High fidelity transparent teleoperation was achieved by using force control with stiffness estimation.
- Motion/force control structure was generalized.
  - Composition of decoupled motion/force control was achieved by constructing selection matrices over multiple control points.
- Contact force consistent control strategy was developed for humanoid systems
  - This enables implementation of motion/force control to non fixed base robots.





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