Robust Haptic Teleoperation of a Mobile Manipulation Platform

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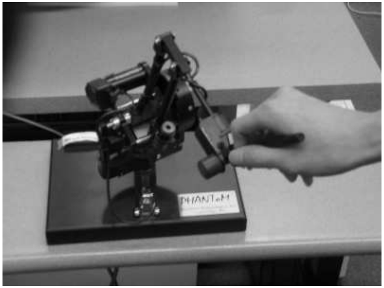
1. System Setup



- Master Haptic Device: PHANTOM 1.0 SensAble
- Slave Mobile Manipulator: PUMA560 on XR4000

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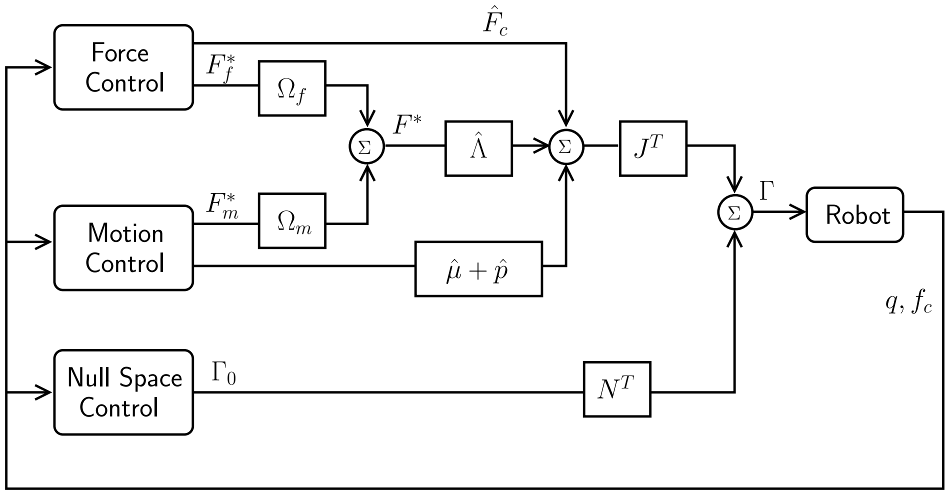
2. Control of a Mobile Manipulator



The equations of motion for the end-effector:

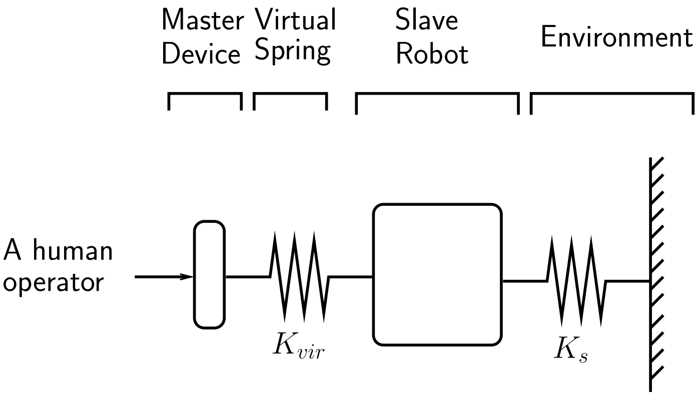
$$\Lambda(q)\dot{\vartheta} + \mu(q,\dot{q}) + p(q) + F_c = F$$

Control:

$$\begin{aligned} \Gamma &= J^T F + N^T \Gamma_0 \\ F &= \hat{\Lambda} F^* + \hat{\mu} + \hat{p} + \hat{F}_c \end{aligned}$$

where $F^* = \Omega_f F_f^* + \Omega_m F_m^*$

3. Teleoperation



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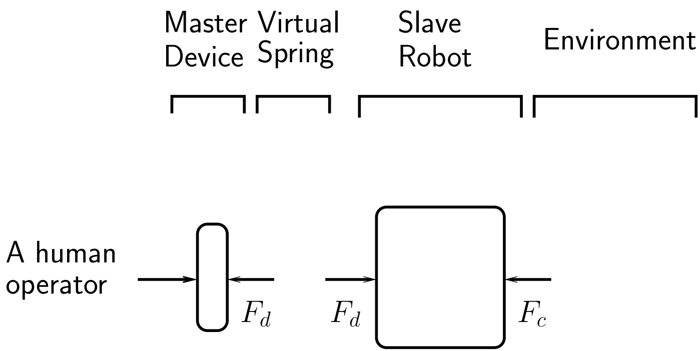

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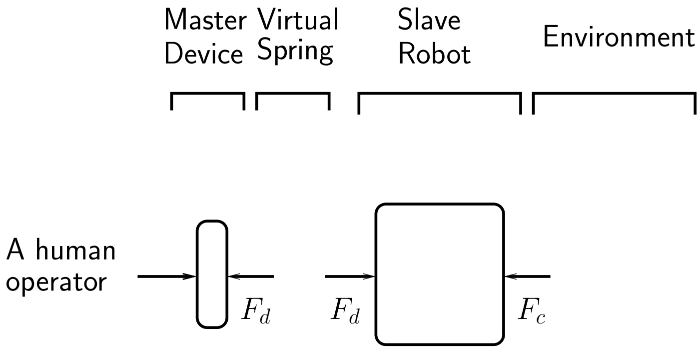
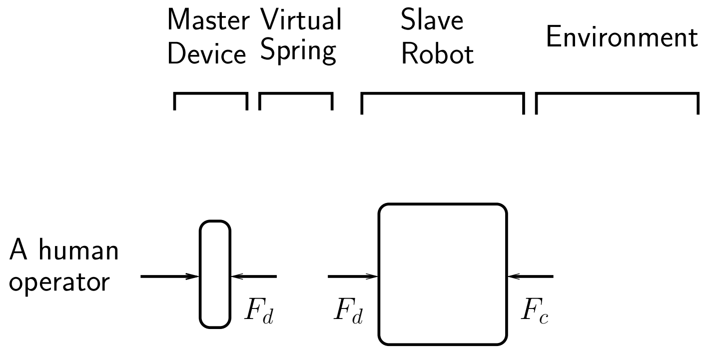


Apply F_d

Force Control makes F_c track F_d

3. Teleoperation



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The human operator feels F_d.

$F_c \approx F_d$

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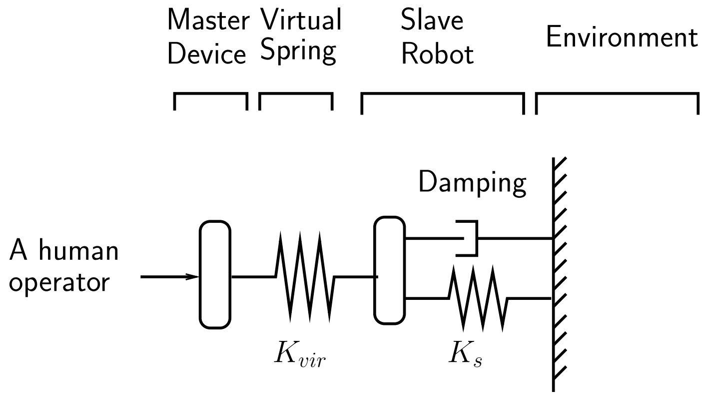

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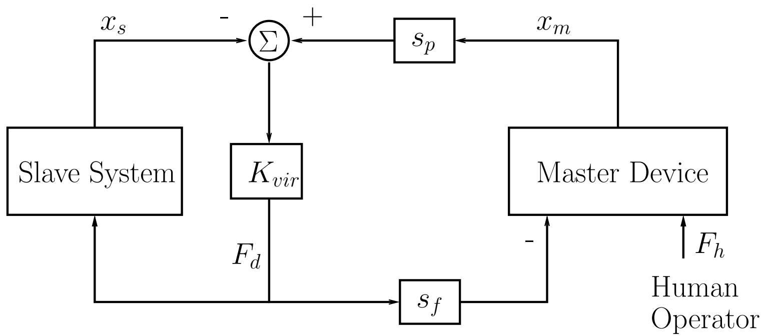
Block Diagram



x_m, x_s	Master and slave position
s_p, s_f	Scaling for position and force
K_{vir}	Virtual spring constant
F_d	Desired contact force for both master and slave

4. Force Control

With the equation of motion for each direction in the operational space coordinate,

$$\dot{\vartheta}_f = F_f^*$$

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The system transfer function can be derived as

$$G(s) = \frac{K_s e^{-sT_d}}{s(s+K_2)}.$$

T_d	system input delay
K_2	additional damping

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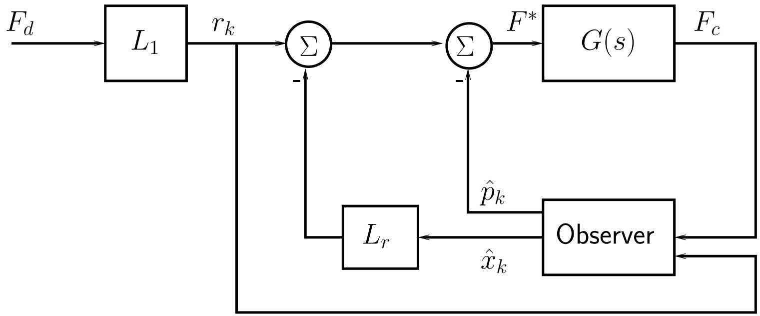
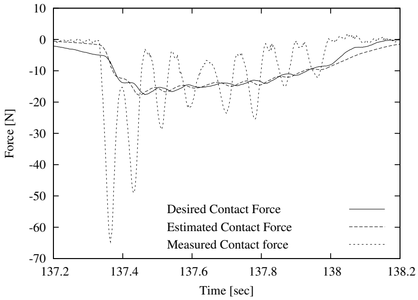
Block Diagram

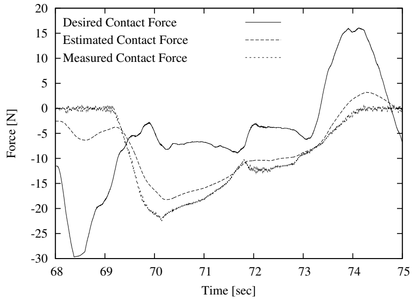


F_c	Contact force at the end-effector
F_d	Desired contact force
F^*	Command input
$\hat{x}_k$	State estimate
$\hat{p}_k$	Input error estimate
r_k, L_1	Reference input, and a scaling factor
L_k	Full state feed-back gain
$G(s)$	System transfer function from F^* to F_c

5. Stiffness Estimation

The results of force control without adaptation





$\hat{K}_s = 100N/m$
K_s changes from
free space to $3000N/m$.

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Adaptation Law

Two Ideas from experiments: $\hat{K}_s^i = \hat{K}_{s,1}^{f,i} + \hat{K}_{s,2}^{f,i}$.

1. Under/Over-estimated K_s shows Different characteristics among the desired, measured, and estimated contact force.

$$\hat{K}_{s,1}^i = \hat{K}_{s,1}^{i-1} + \Delta\hat{K}_{s,1}^i,$$

where

$$\begin{aligned}\Delta\hat{K}_{s,1}^i &= k_1|F_m - F_e|\,\sigma_d\left(c, \frac{|F_m - F_e|}{|F_e| + a_1} - b_1\right)\\ &\quad -k_2|F_d - F_e|\,\sigma_d\left(c, \frac{|F_d - F_e|}{|F_e| + a_2} - b_2\right),\\ \sigma_d(c,x) &= \frac{1}{1+e^{-cx}}.\end{aligned}$$

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2. System stiffness, K_s, increases with the applied contact force.

$$\hat{K}_{s,2} = K_{min} + k_3\,\sigma_d\left(c_0, |F_m| - F_0\right).$$

6. Experimental Results

- Position Scale from Haptic Device to PUMA : 2.0
- Force Scale from PUMA to Haptic Device : 0.1
- Time Delay in communication : about 26 ms in one direction

- System Setup
- Control of a Mobile...
- Teleoperation
- Force Control
- Stiffness Estimation
- **Experimental Results**
- Conclusion
- Juliet Setting a Dinner...

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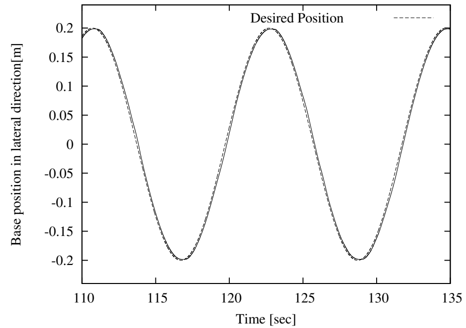
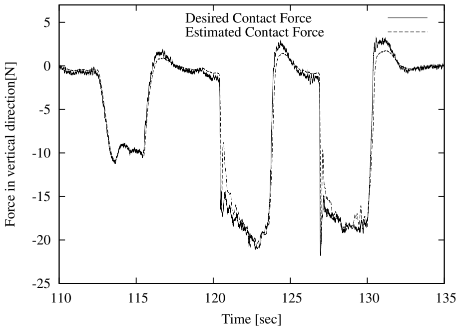
Moving base teleoperation: Base Motion

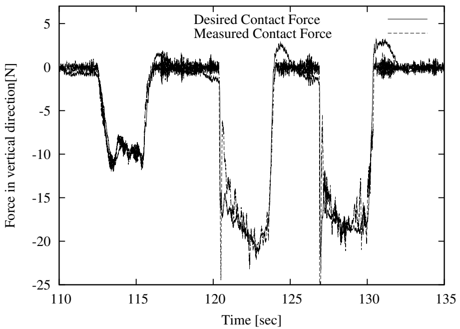


Base motion in the lateral direction(i.e. along the table)
The amplitude is 20 cm and the period is 12 seconds.

Moving base teleoperation: force response

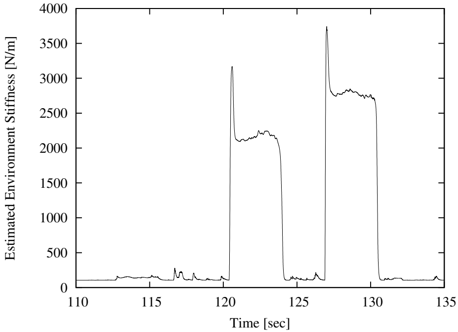


Desired and Estimated Contact Force

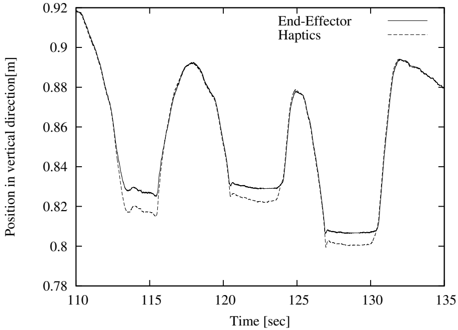


Desired and Measured Contact Force

Moving base teleoperation: $\hat{K}_s$ and position tracking

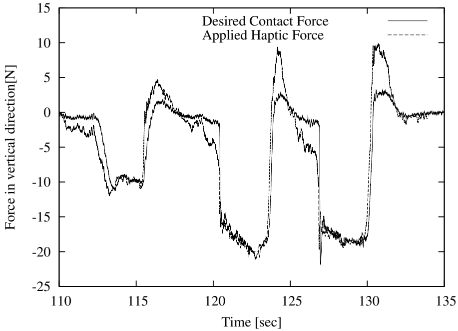


Estimated Environment Stiffness

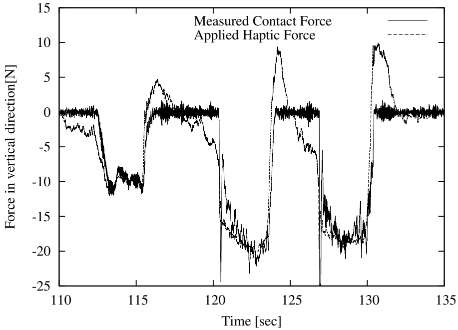


End-effector Tracking Haptic Device Position

Moving base teleoperation: force comparison



Desired Contact Force and Applied Haptic Force to User



Measured Contact Force and Applied Haptic Force to User

7. Conclusion

- Simple teleoperation scheme using an adaptive force control
- Robust force control using AOB(i.e. a modified Kalman estimator)
- Fast On-line stiffness adaptation
- Decoupled control strategy for a mobile manipulator.

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Future Work

- More systematic algorithm for stiffness adaptation
- Better user interface for redundant DOF of a mobile manipulator

8. Juliet Setting a Dinner Table