Multi-Contact Compliant Motion Control for Robotic Manipulators

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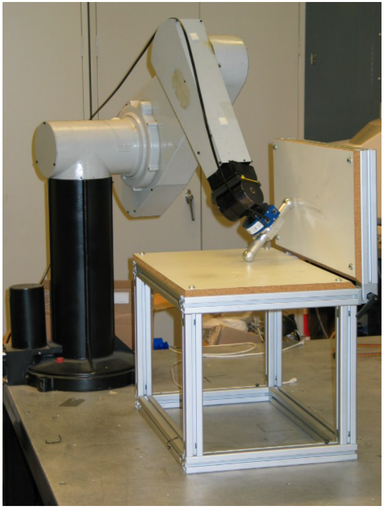
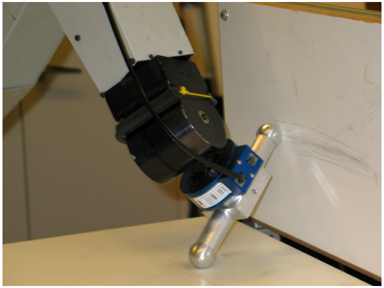
1. System Setup





- PUMA560
- Two contacts with vertical board and horizontal table

2. Motivation

Multi-Contact Formulation

- Our previous work[1] developed a general multi-contact model, which cannot be described by the Raibert-Craig model.[2]
- Extend the framework by modeling the stiffness of the environment.

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Force Control

A modified Kalman estimation(AOB) is well suited for our system.

- Uncertain input torque - additional input error state.
- Varying measurement noise - on-line variance calculation.

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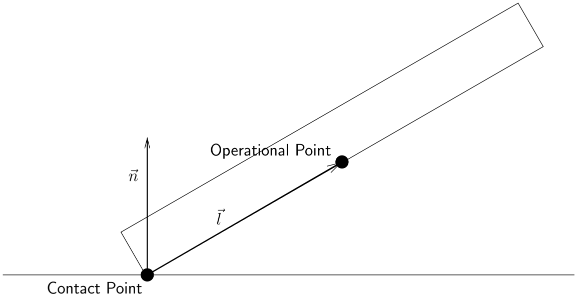
[1] Roy Featherstone, Stef Sonck Tiebaut, and Oussama Khatib. A general contact model for dynamically decoupled force/motion control, 1999.

[2] Raibert, M. H., and Craig, J. J. Hybrid Position/Force Control of Manipulators, ASME Jnl. Dynamic Systems, Measurement & Control, 1981

3. Multi-Contact Formulation

Multi-Contact model

$$
\begin{aligned}
f_c &= N\alpha \\
N &= \begin{bmatrix} \vec{n} \\ \vec{n} \times \vec{l} \end{bmatrix} \\
\alpha &: \text{magnitude of contact force}
\end{aligned}
$$



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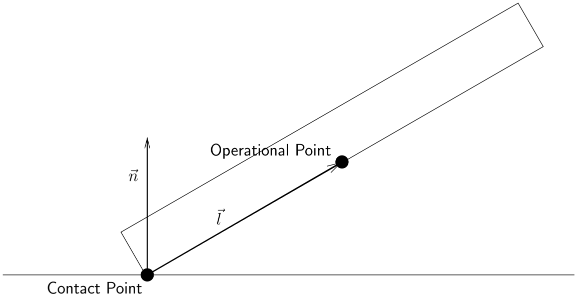
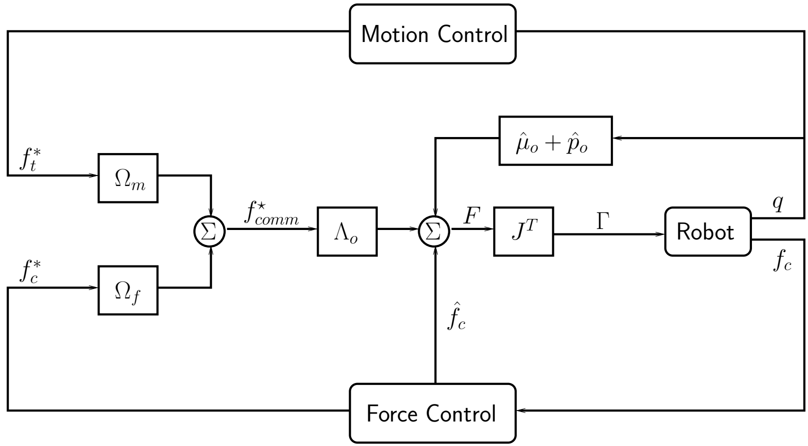


Projection Matrices

$$
\begin{aligned}
f_c &= \Omega_f f \\
\vartheta_t &= \Omega_m \vartheta
\end{aligned}
$$

ϑ	velocity of the operational point
f	force at the operational point
N	spans contact normal space

4. Control



Equations of Motion with Operational Space Formulation

$$\Lambda_o(x)\dot{\vartheta} + \mu_o(x,\vartheta) + p_o(x) + f_c = F,$$

$$\begin{aligned} F &= f^\star_{com} + \hat{\mu}_o(x,\vartheta) + \hat{p}_o(x) + \hat{f}_c \\ f^\star_{com} &= \Lambda_o \Omega_m f_t^* + \Lambda_o \Omega_f f_c^*. \end{aligned}$$

Force control

With equations of motion in *Contact Normal Space*

$$\dot{\vartheta}_c \quad = \quad \Omega_f f_c^\star$$

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With equations of motion in *Contact Normal Space*

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and a spring model

$$\dot{f}_{c,i} = k_{s,i} \vartheta_{c,i},$$

Force control

With equations of motion in *Contact Normal Space*

$$\dot{\vartheta}_c = \Omega_f f_c^\star$$

and a spring model

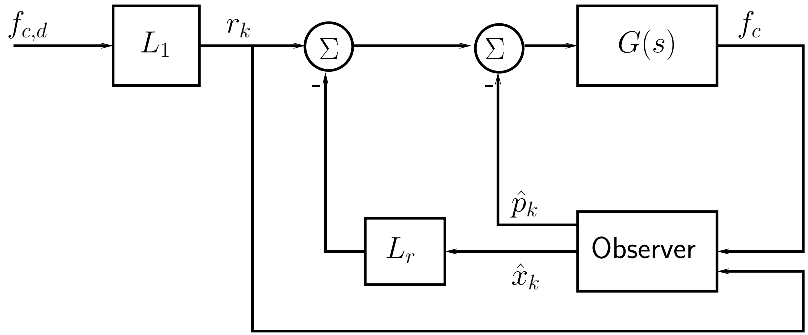
$$\dot{f}_{c,i} = k_{s,i} \vartheta_{c,i},$$

The system transfer function can be derived as

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

T_d	system input delay
K_2	additional damping

Force control Design



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
$\hat{x}_k$	state estimate
$\hat{p}_k$	input error estimate

Noise Variance(R_k) Estimation

- The discrete time first order high-pass filter

$$\alpha_f(z) = G_f(z)\alpha(z),$$

$G_f(z)$	the filter with a zero at 3[Hz] and a pole at 60[Hz]
$\alpha(z)$	the measured contact force for each contact force space

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- The estimation of the measurement noise, $\hat{R}(t_i)$

$$\hat{R}(t_i) = \frac{1}{N}\sum_{j=i-N+1}^{i}\{[\alpha_f(t_j) - \bar{\alpha}_f][\alpha_f(t_j) - \bar{\alpha}_f]^T\},$$

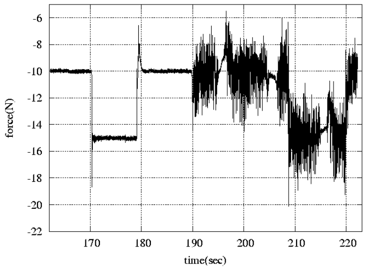
where $\bar{\alpha}_f$ is the mean of the filtered force over a time window.

- 50 samples have been used in the experiments.

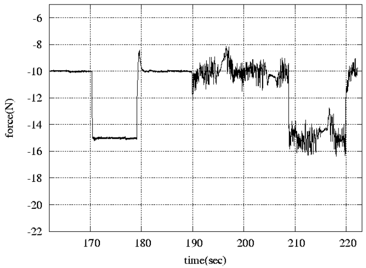
5. Results

Experiment for Analysis

Measured and Estimated forces in contact with the table.

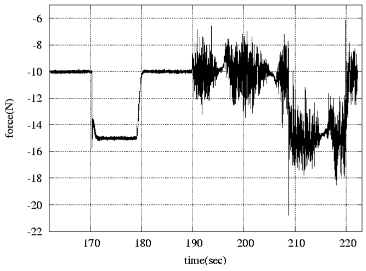


(a) Measured force of the first contact. z direction.

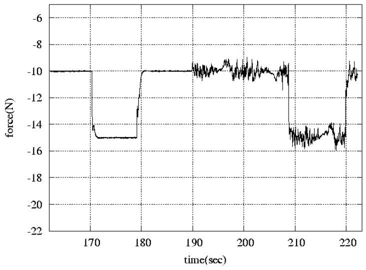


(b) Estimated force of the first contact. z direction.

Measured and Estimated forces in contact with the vertical board.

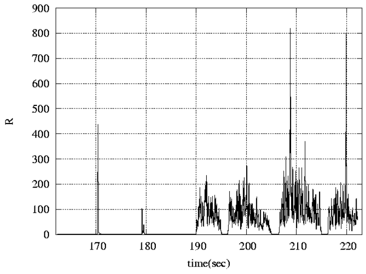


(a) Measured force of the second contact. y direction.

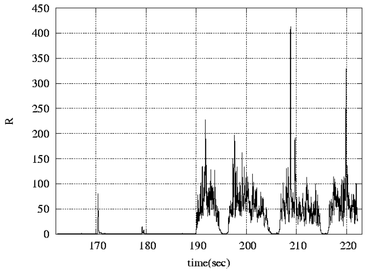


(b) Estimated force of the second contact. y direction.

Noise Variance Estimations.

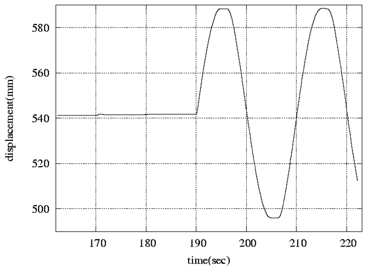


(a) Noise Covariance Estimation for the first contact force.



(b) Noise Covariance Estimation for the second contact force.

Wrist translational motion in x direction.



6. Movie

Linear/Angular Motion with Contacts (90/120 degree)

Without/With online calculation of Noise Variance, R_k

7. Conclusion

Multi-Contact Formulation

- Extend our previous work(multi-contact motion/force control for rigid contact) to deal with compliant contact.
- This new formulation sets up dynamic equation for contact force control.

Force Control

- Apply a modified Kalman filter estimator(AOBs).
- On-line noise Estimation.

8. Future Work

- More experiments with different stiffness environment.
- Implement on-line stiffness estimation strategy.
- Multi-contact with multi-link.