Precise Positioning and Compliance Synthesis for Automatic Assembly Using Lorentz Levitation

R. L. Hollis* and S. Salcudean+

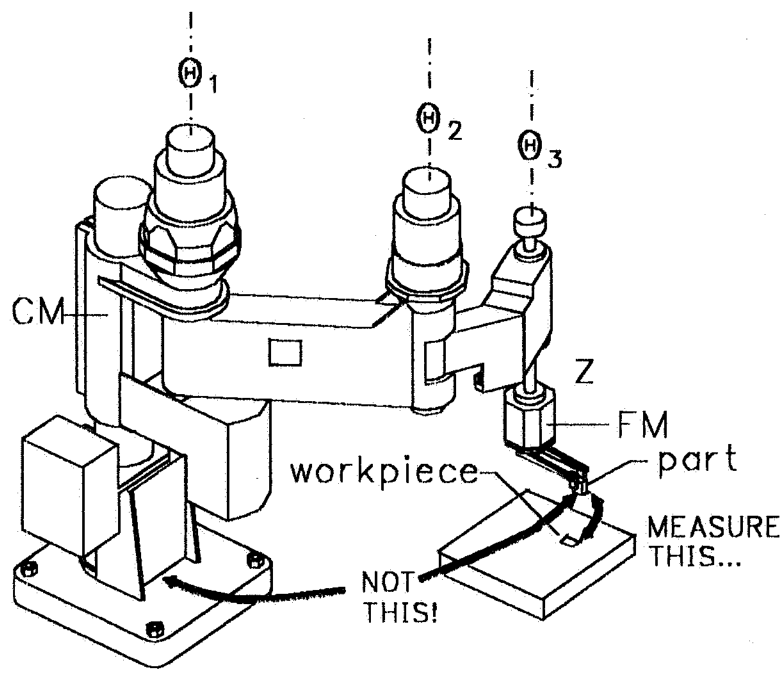
*IBM Research Division
Thomas J. Watson Research Center
Yorktown Heights, NY 10598 USA

+Department of Electrical Engineering
University of British Columbia
Vancouver, B.C., Canada

Abstract

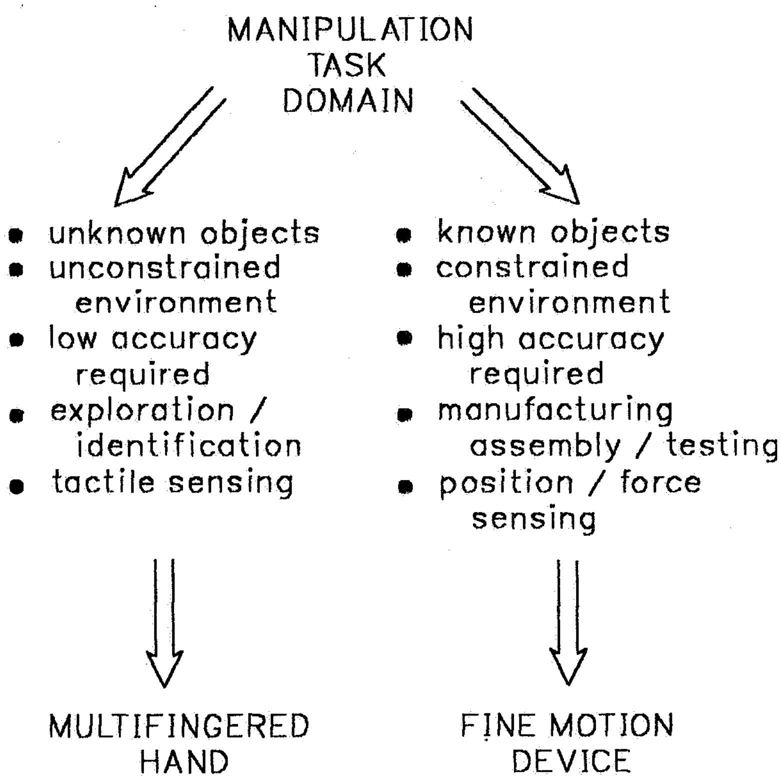
Many manufacturing assembly tasks require fine compliant motion and fast, accurate positioning. Conventional robots perform poorly in these tasks because of their large mass, friction and backlash in gears, cogging in drive motors and other deleterious effects. Even robots equipped with special control systems enabling compliant operation offer only partial solutions. It is therefore difficult or impossible to automate many product assemblies requiring fine, compliant motion. This problem can be greatly alleviated by dividing the manipulation system into coarse and fine domains. In this scenario, a standard industrial robot can serve as a coarse positioner which in turn carries a six-degree-of-freedom fine motion wrist. Thus the robot can access a workspace measured in meters at low bandwidth and low resolution while the wrist can move over millimeters at high bandwidth and high resolution during the final phases of the assembly operation. Our work indicates that fine motion wrists using Lorentz levitation can greatly augment the accuracy and dexterity of robots because they are frictionless, have high bandwidths and have a single back-drivable moving part. Additionally, since there is no contact between the moving and stationary parts, wear and contamination can be eliminated. The use of six Lorentz force actuators in combination with realtime position and orientation sensing offers several important advantages over magnetic bearing approaches.

Coarse-Fine Manipulation



A standard industrial robot can be used as a coarse manipulator (CM) operating in tandem with a specially designed fine manipulator (FM) to obtain a system with large motion range, very high motion resolution, and high bandwidth. The FM carries out manipulation tasks under the guidance of endpoint sensors based on vision, optics, capacitance, inductance, etc. to carry out closed-loop assembly.

Two Manipulation Scenarios



In coarse-fine manipulation, choices can be made between using multi-fingered hands or fine motion devices. The manufacturing environment favors the use of fine motion devices. Fine motion devices must be designed to overcome the problems inherent in the coarse robot: poor resolution, large inertias, static friction in the joints, link bending, etc.

Design Principles for Fine Motion Devices

- **P1** MASS: lowest total mass → minimal effect on coarse manipulator performance
- **P2** ACCELERATION: highest force to moving mass ratio → high bandwidth, high throughput and vibration rejection capability
- **P3** STRUCTURE: single moving element which approaches a rigid body → elimination of structural modes and complex dynamic effects
- **P4** COLOCATION: closest proximity of endpoint, actuation means, and sensing means → elimination of phase lags and actuator-sensor dynamics
- **P5** STICTION: frictionless suspension or bearing systems → elimination of stick-slip limit cycles, wear, and contamination
- **P6** SENSING: noncontact internal position sensing → good closed loop control even in the absence of endpoint sensing information

Lorentz Levitation

- **Magnetic Bearings**

  Suspension by controlled DC electromagnets and the force of attraction between magnetized bodies

  Principal advantage:

  — $\simeq 10 \times$ more efficient than Lorentz levitation

- **Lorentz Levitation**

  Levitation by forces due to controlled currents in conductors in magnetic fields

  Principal advantages:

  — greatly reduced suspended mass — no floating iron

  — single coil provides bi-directional forces

  — no need for "bias" currents★

  — essentially linear current *vs.* force property★

  — essentially constant force *vs.* position property

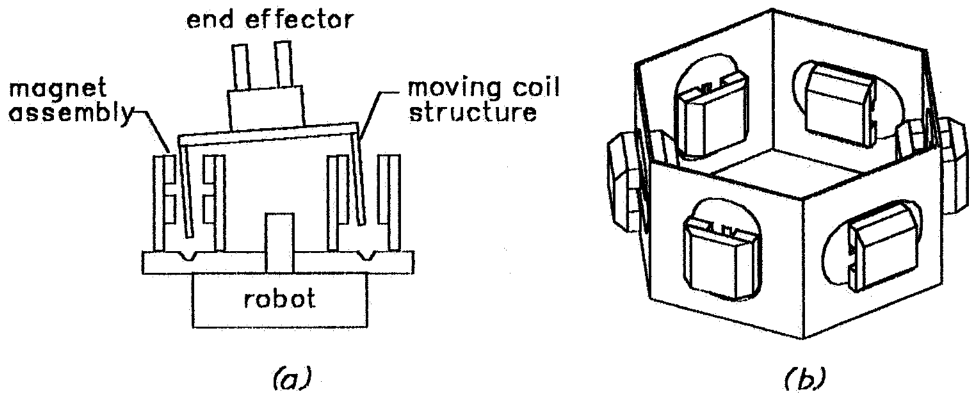
  — greatly reduced coil inductance — fast response

  — force generated is approximately in plane of coil

  — reduced hysteresis and iron loss

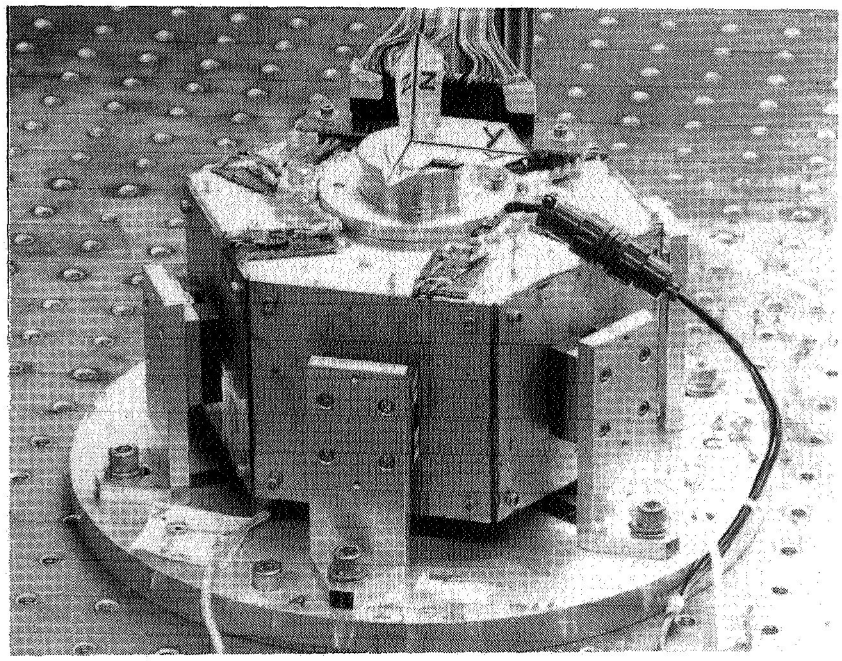
  — very high momentary forces possible

★also true of new hybrid-type magnetic bearings



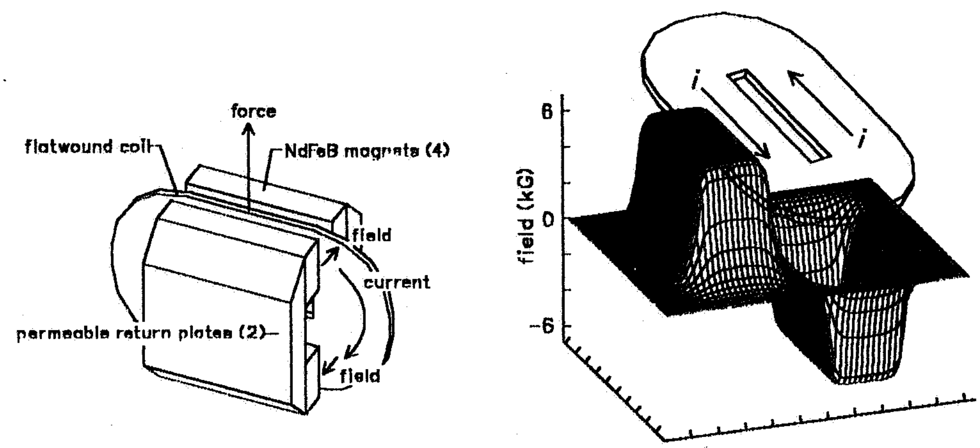
(a) Cross-sectional view, (b) general view.

Magic Wrist Prototype



The prototype magic wrist operates on a benchtop. It can position in six degrees of freedom with a resolution of about 1 μm in translation, and 0.00001° in rotation over a workspace of ±5 mm in translation and ±4° in rotation. A steady-state load of 32.5 N (7.3 lb.) can be supported with a power expenditure of 60 W.

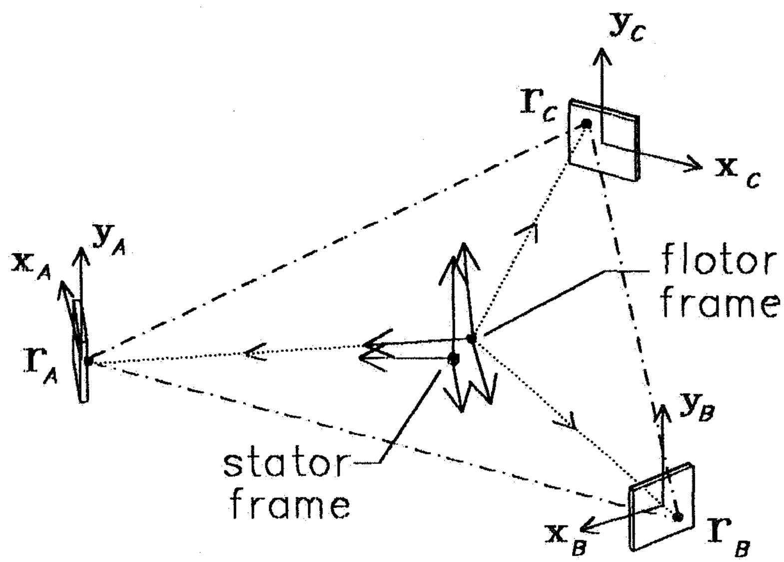
A robot-mountable version of the wrist is nearing completion.



(a) (b)

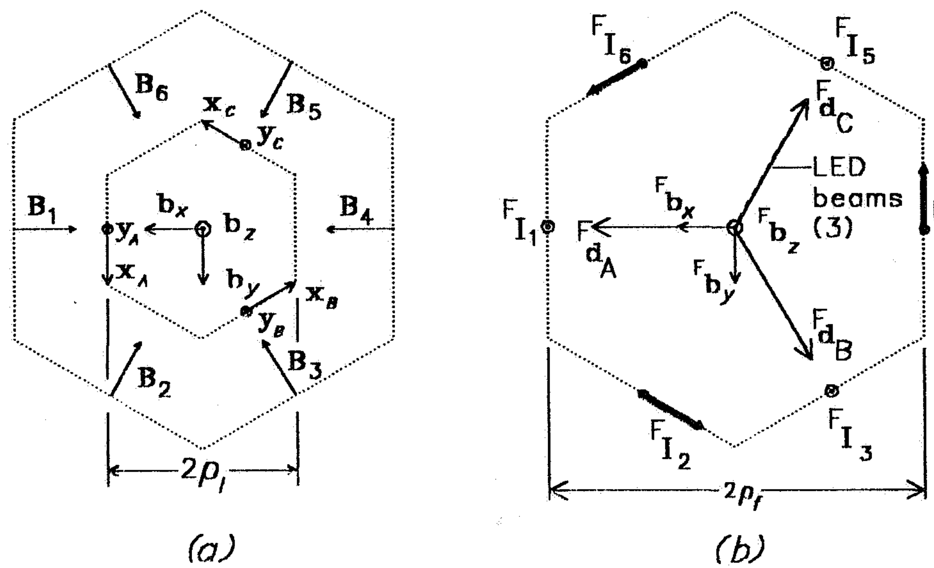
(a) Flat coil large-gap Lorentz actuator, (b) calculated normal component of the magnetic field.

The wrist uses six actuators of this type to produce an arbitrary force/torque vector on the flotor. In the magic wrist, there is a trade-off between high magnetic efficiency with a narrow gap *vs.* the necessity of allowing substantial free motion in all six degrees of freedom, *i.e.*, achievable force *vs.* workspace size.



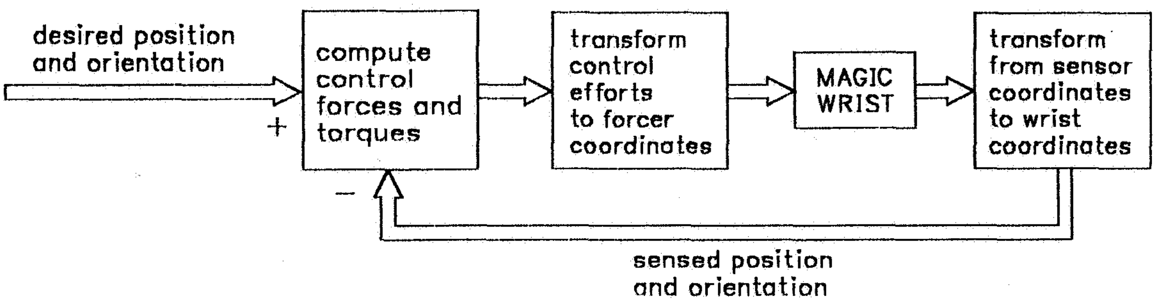
Internal position sensors. Three radial light beams fall on a set of three two-dimensional PSDs to give complete position and orientation sensing.

Stator and Flotor Coordinate Frames



(a) Stator frame vectors. The magnetic field vectors and the PSD coordinate systems are fixed in the wrist stator. (b) Wrist frame vectors. The coil currents and LED beams are fixed in the wrist flotor.

Dynamics and Control



Euler parameter vector

$$\mathbf{p} \triangleq [\beta_0 \ \ \boldsymbol{\beta}^T]^T = [\ \cos(\phi/2) \ \ \sin(\phi/2) \ \ \mathbf{s}^T]^T \ ,$$

where $\mathbf{s}$ is the axis of rotation ($\|\mathbf{s}\| = 1$) and ϕ is the angle of rotation.

Task space linear dynamics

$$\ddot{\boldsymbol{\beta}} = \frac{1}{2} \ {}^F\dot{\omega} = \frac{1}{2} \ {}^F J^{-1} \, {}^F\tau \triangleq \mathbf{u}_1$$

$$\ddot{\mathbf{r}}_T = \frac{1}{m} \ \mathbf{f} + \mathbf{g} - {}^F\mathbf{r}_T \times \ {}^F J^{-1} \, {}^F\tau \triangleq \mathbf{u}_2 \ \ .$$

PD control law

$$\mathbf{u}_1 = K_p \, (\boldsymbol{\beta}_d - \boldsymbol{\beta}) - K_v \, \dot{\boldsymbol{\beta}}$$

$$\mathbf{u}_2 = \tilde{K}_p \, (\mathbf{r}_d - \mathbf{r}_T) - \tilde{K}_v \, \dot{\mathbf{r}}_T$$

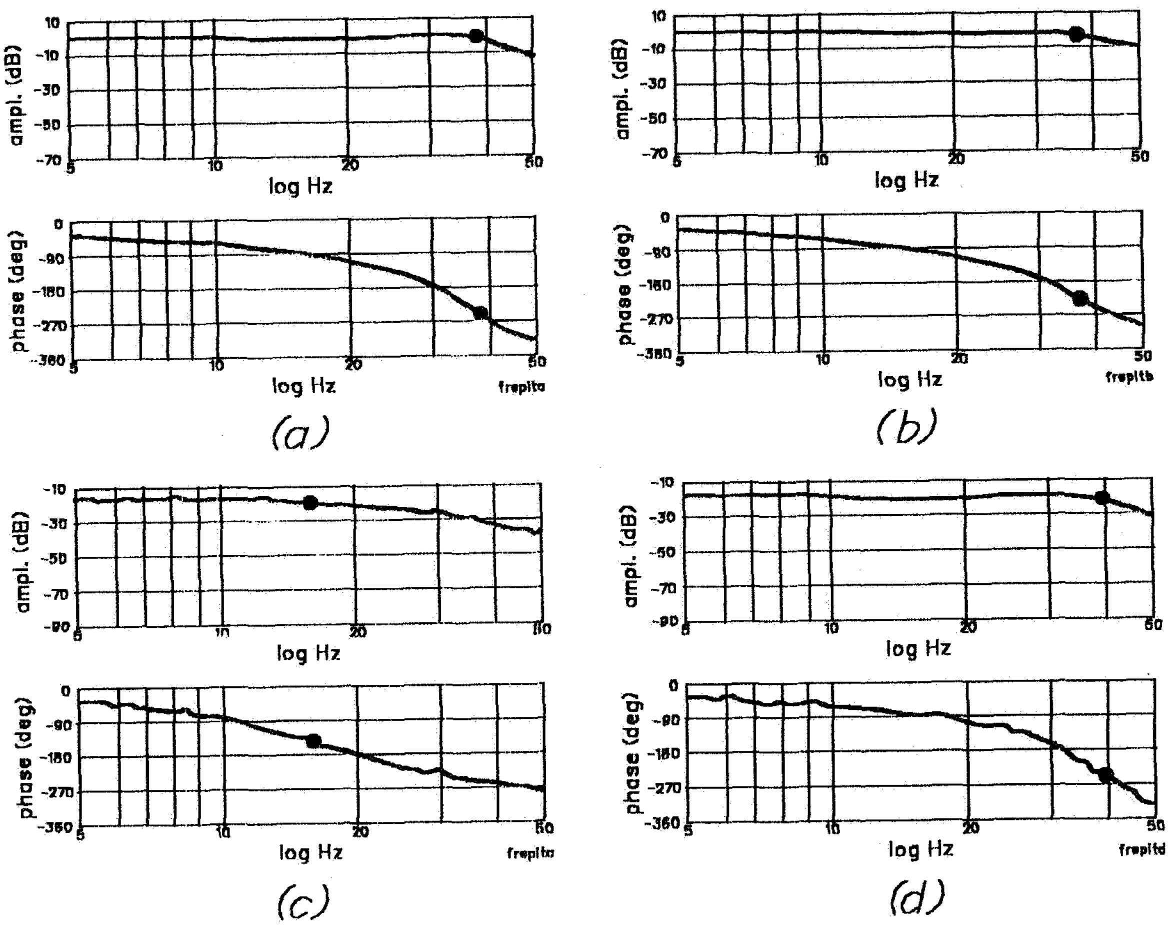
Gain matrices

$$K_p \triangleq R^T \, diag(k_{p1}, k_{p2}, k_{p3}) \, R$$

$$K_v \triangleq R^T \, diag(k_{v1}, k_{v2}, k_{v3}) \, R$$

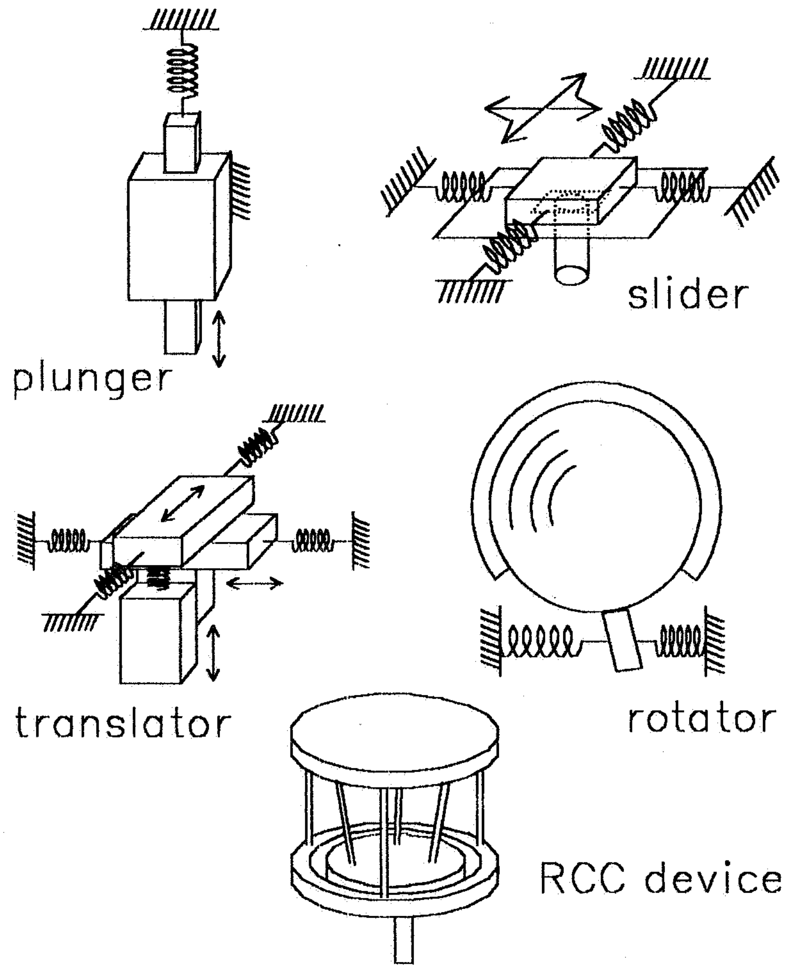
$$\tilde{K}_p \triangleq \tilde{R}^T \, diag(\tilde{k}_{p1}, \tilde{k}_{p2}, \tilde{k}_{p3}) \, \tilde{R}$$

$$\tilde{K}_p \triangleq \tilde{R}^T \, diag(\tilde{k}_{v1}, \tilde{k}_{v2}, \tilde{k}_{v3}) \, \tilde{R} \ .$$



Frequency responses. (a) translation along the x axis, (b) translation along the z axis, (c) rotation about the x axis, (d) rotation about the z axis.

Mechanism Emulation



By varying the control gains, the magic wrist can emulate various mechanisms.

Published Material

- "A Six Degree-of-Freedom Magnetically Levitated Variable Compliance Fine Motion Wrist: Design, Modelling and Control," R. L. Hollis, S. Salcudean, and A. P. Allan, *IEEE Transactions on Robotics and Automation* 7[3], June 1991, pp. 320-332.
- "On the Design and Control of Magnetically Levitated Robot Wrists," R. L. Hollis and S. Salcudean, *Proc. 3rd Int'l Symposium on Robotics and Manufacturing*, Vancouver, B.C., July 18-20, 1990.
- "Toward a Tele-nanorobotic Manipulation System with Atomic Scale Force Feedback and Motion Resolution," R. L. Hollis, S. Salcudean, and D. W. Abraham, *Proc. Third IEEE Workshop on Micro Electro Mechanical Systems*, Napa Valley, CA, Feb. 12-14, 1990, pp. 115-119.
- "A Magnetically Levitated Fine Motion Wrist: Design and Feasibility Experiments," R. L. Hollis and A. P. Allan, *ASME Winter Annual Meeting*, Chicago, Illinois, Nov. 27 - Dec. 2, 1988, published in **Symposium on Robotics** , DSC Vol. 11, ed. by K. Youcef-Toumi and H. Kazerooni, ASME, pp. 343 - 352.
- "A Magnetically Levitated Fine Motion Wrist: Kinematics, Dynamics, and Control," S. Salcudean and R. L. Hollis, *Proceedings of the IEEE International Conference on Robotics and Automation*, pp. 261-266, Philadelphia, PA, April 24-29, 1988.
- "A Six Degree-of-Freedom Magnetically Levitated Variable Compliance Fine Motion Wrist," R. L. Hollis, A. P. Allan, and S. Salcudean, *4th International Symposium on Robotics Research*, Santa Cruz, Ca., August 9-14, 1987, published in **Robotics Research** vol. 4, pp. 65-73, ed. by R. Bolles and B. Roth, MIT Press.