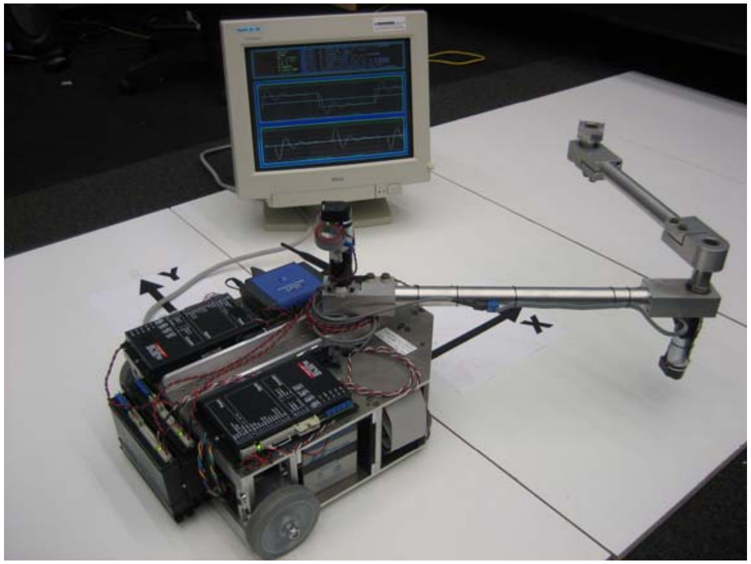
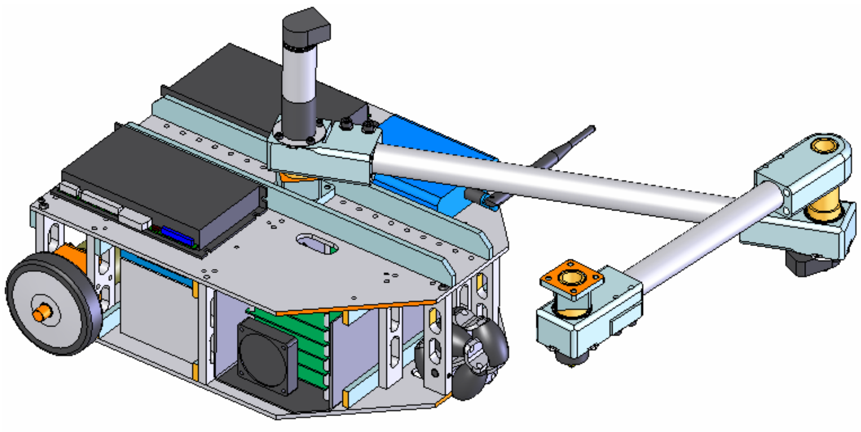
Decoupled Dynamic Control of a Nonholonomic Wheeled Mobile Manipulators





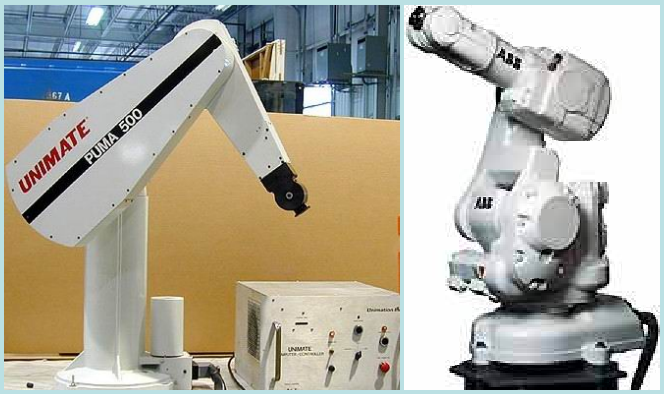
Chin Pei Tang (chintang@eng.buffalo.edu)
Venkat Krovi (vkrovi@eng.buffalo.edu)

Mechanical and Aerospace Engineering
State University of New York at Buffalo

Acknowledgment:
Rajankumar Bhatt
Glenn D. White

Motivation

Mobile manipulator systems are useful in extending the reach of humans in many manipulation & environment interaction tasks.



Fixed-Base Serial Robotic Manipulator

+

Wheeled Mobile Robots

Combined Capabilities

Wheeled Mobile Manipulators

Applications: Payload manipulation, arc welding, highway maintenance, mining, explosive/hazardous materials disposal, etc.

Advantages

Combined DOF can reach much larger workspace.

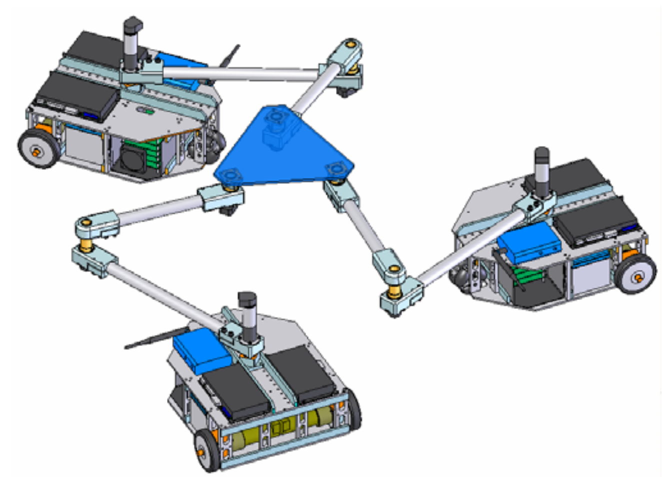
– ***Manipulator*** is typically more dexterous and can perform finer motion with greater performance.
– ***Mobile base*** provides the mobility and carries the load of the manipulator so that it can reach any point in the plane.

Redundancy in configuration.

– Flexibility to perform more complex and different tasks.
– Ability to mechanically accommodate, detect, and compensate for disturbances.

Our ultimate goal:

Cooperative payload transport by multiple wheeled mobile manipulators.



Each module =

Differentially-driven wheeled mobile robot
+ planar RR manipulator

Research Issues

Design:

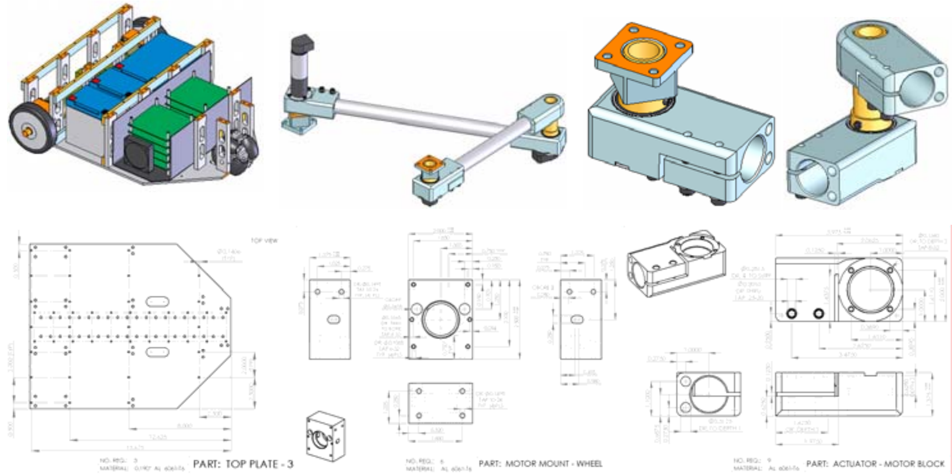
- Topology, dimensions, actuation
- Physical prototype realization

Control:

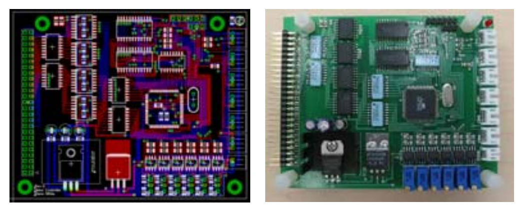
- Redundancy resolution schemes (kinematic/dynamics)
- Disturbance compensation/rejection

Validation:

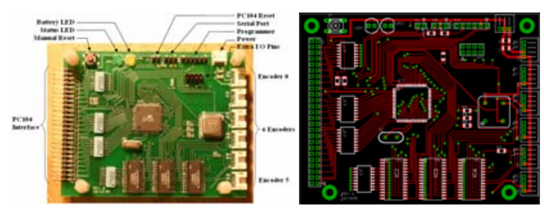
- Electronics subsystems design
- Hardware-in-the-loop (HIL)
- Virtual prototyping/co-simulations



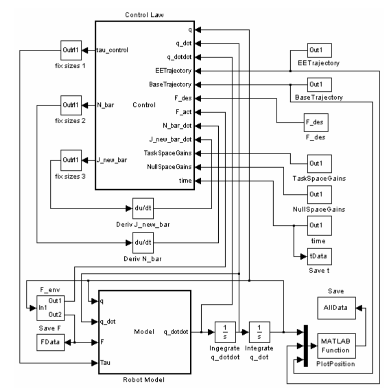
Mechanical Prototype Realization



Motor Controller

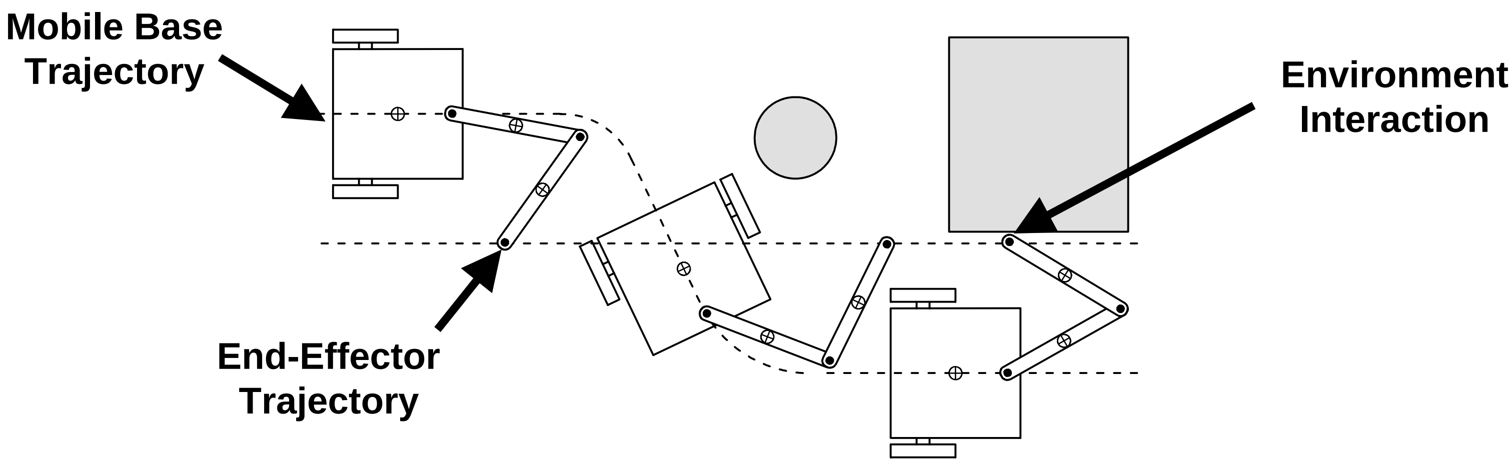


Encoder Coprocessor



Redundancy Resolution Algorithms

Scenario



Challenges

- *Nonholonomic constraints* due to wheel assemblies.
- The *dynamic interaction* between the manipulator and the mobile base is highly coupled (in both motions and forces)
- Combining mobility of the wheeled platform and mounted manipulator creates both *kinematic and actuator/dynamic redundancy*.

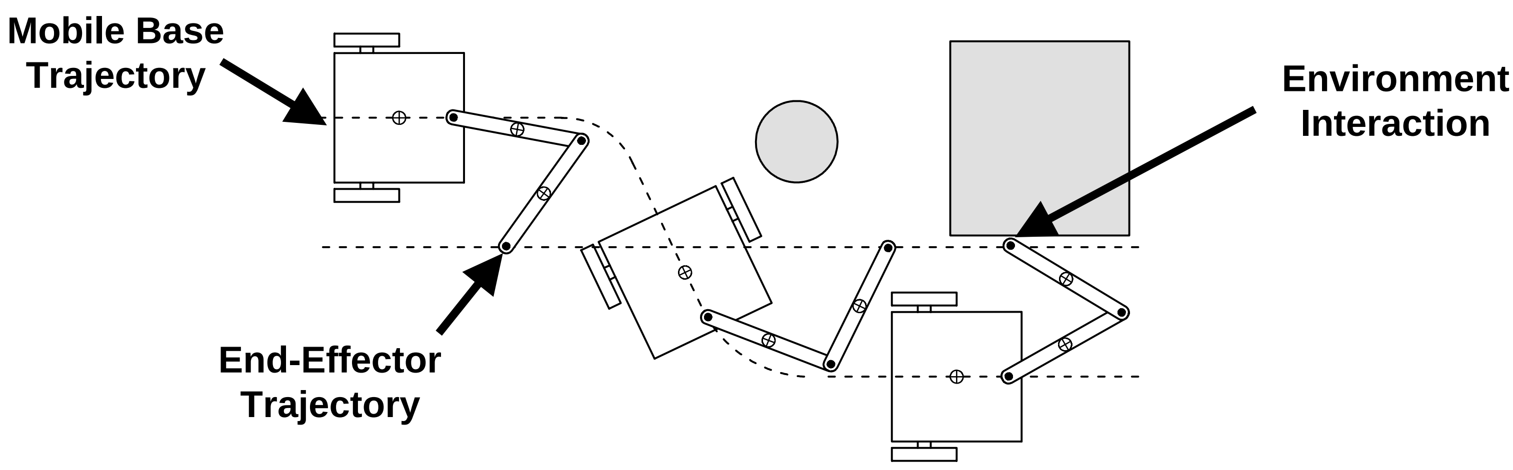
Our Focus

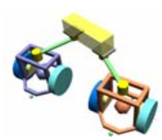
Decoupling the system dynamics into task-space and null-space components...

…such that:

– the *primary* and *secondary objectives* can be achieved independently in a *dynamically consistent sense*

– …while taking into account of *nonholonomic constraints*.





Dynamic Modeling

Constrained Dynamic Equation

with extended generalized coordinates

$$M(\underline{q})\ddot{\underline{q}} + V(\underline{q},\dot{\underline{q}}) = E\underline{\tau}_m + E_2\underline{F} - A^T\underline{\lambda}$$

$$\underline{q} = \begin{bmatrix} x_c & y_c & \phi & \theta_R & \theta_L & \theta_1 & \theta_2 \end{bmatrix}^T$$

Nonholonomic Constraints

$$A(\underline{q})\dot{\underline{q}} = 0$$

S^T **Projection** $S^T A^T = 0$

Feasible Dynamic Equation

with minimal generalized coordinates

$$S^T M S\dot{\underline{\nu}} + S^T M\dot{S}\underline{\nu} + S^T V = S^T E\underline{\tau}_m + S^T E_2\underline{F}$$

$$\underline{\nu} = \begin{bmatrix} \dot{\theta}_R & \dot{\theta}_L & \dot{\theta}_1 & \dot{\theta}_2 \end{bmatrix}^T$$

Standard Form (via Change of Variables):

$$H\ddot{\underline{z}} + C\dot{\underline{z}} + g = \underline{\tau} + \underline{\tau}_E$$

$$\dot{\underline{z}} = \underline{\nu}, \ddot{\underline{z}} = \dot{\underline{\nu}}$$

External (End-Effector) Forces

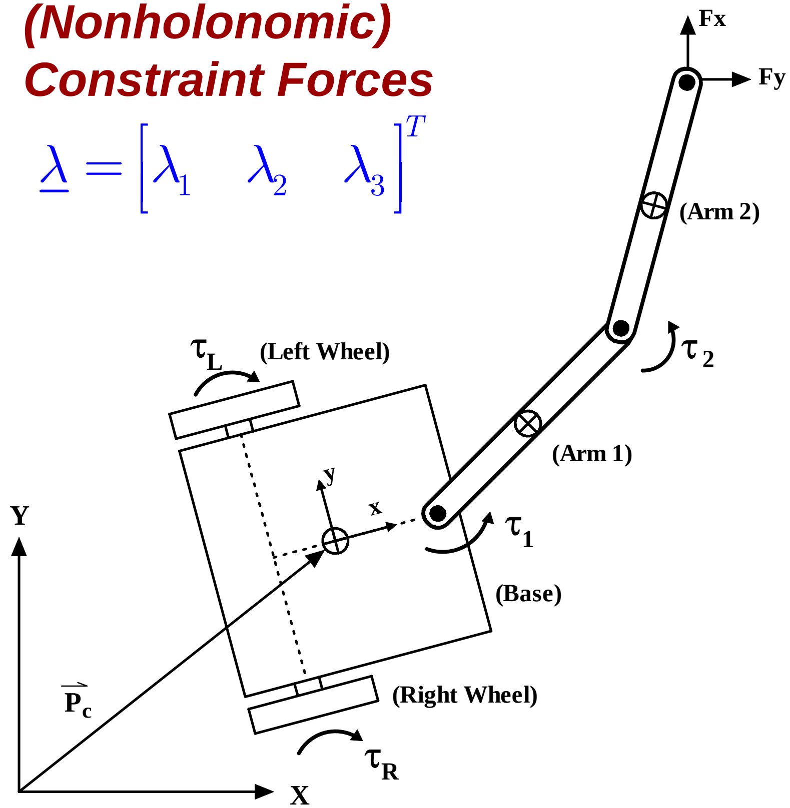
$$\underline{F} = \begin{bmatrix} F_x & F_y \end{bmatrix}^T$$

Joint Actuations

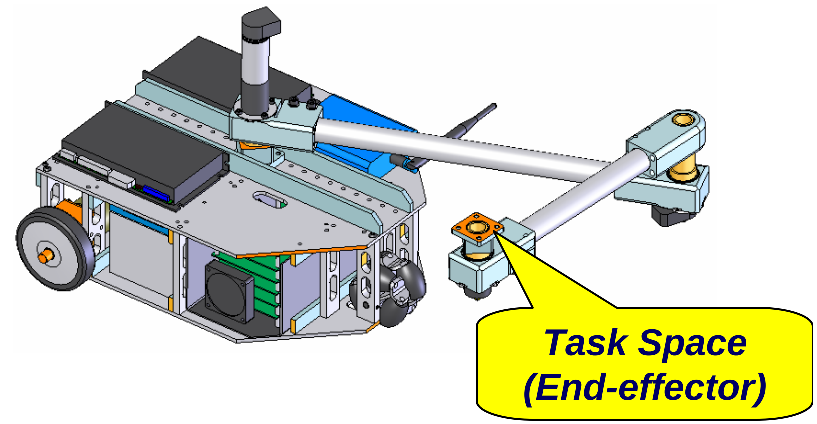
$$\underline{\tau}_m = \begin{bmatrix} \tau_R & \tau_L & \tau_1 & \tau_2 \end{bmatrix}^T$$

(Nonholonomic) Constraint Forces

$$\underline{\lambda} = \begin{bmatrix} \lambda_1 & \lambda_2 & \lambda_3 \end{bmatrix}^T$$



Redundancy Resolution Approach



- Identifying two spaces:
  - ***Task-space*** (End-effector)
  - ***(Internal) configuration-space*** (Mobile base configuration)
- ***Projection*** of dynamic equations into decoupled task- and null-spaces ensuring dynamic consistency
- Creates inputs for each using ***nonlinear feedback***
- Extends methods for redundant holonomic manipulators to the mobile manipulators
- Advantages:
  - Development and linear superposition of ***independent task-*** and ***null-space controllers***.
  - ***Guaranteeing task achievement*** in the event of the task-space and configuration-space ***trajectories conflict***.

Dynamic Redundancy Resolution

Mapping between
joint space (n dim)
to
task space (p dim)

$$\underline{\dot{x}}_p = J\underline{\dot{z}}_n$$

Kinematic Redundancy Resolution Schemes

Velocity (rate) level $\underline{\dot{z}} = J^{\#}\underline{\dot{x}} + N\underline{\dot{z}}_h$

Acceleration level $\underline{\ddot{z}} = J^{\#}\left(\underline{\dot{x}} - J\underline{\dot{z}}\right) + N\underline{\ddot{z}}_h$

Special Case: Take “Dynamically Consistent Pseudoinverse”

$$J^{\#} = \bar{J} = H^{-1}J^T\left(JH^{-1}J^T\right)^{-1} \qquad N^T = \overline{N}^T = I - J^T\overline{J}^T$$

Decoupled (Minimal) Joint Space Dynamics:

$$J^T\underline{F} + \bar{N}^T\underline{\tau} = J^T\bar{J}^T\left(H\bar{J}\left(\underline{\ddot{x}} - \dot{J}\underline{\dot{z}}\right) + C\underline{\dot{z}} + g - \underline{\tau}_E\right) + \bar{N}^T\left(H\bar{N}\left(\underline{\ddot{z}}\right) + C\underline{\dot{z}} + g - \underline{\tau}_E\right) + J^T\bar{J}^T H\bar{N}\underline{\ddot{z}} + \bar{N}^T H\bar{J}\left(\underline{\ddot{x}} - \dot{J}\underline{\dot{z}}\right)$$

Task Dynamic | **Null (Internal) Dynamic** | **Coupling** → 0

Total Input Torque:

$$\underline{\tau} = J^T W\left(\underline{u} - \dot{J}\underline{\dot{z}}\right) + \overline{N}^T H\left(\underline{v} + \dot{\bar{J}}\underline{\dot{x}}\right) + C\underline{\dot{z}} + \underline{g} + J^T\underline{F}_E$$

Task Space Control | **Null (Internal) Space Control**

Task and Internal Space Control

The control laws for task space and null (internal) space can now be designed independently.

Task-Space Control

[Primary Control Space]

- **External task space control that primarily achieves the tracking of end-effector motion/force with performance guarantees.**

Task Space Dynamics:

$$W(\underline{z})\ddot{\underline{x}} + \underline{\mu}(\underline{z},\dot{\underline{z}}) + \underline{\gamma}(\underline{z}) = \underline{F} + \underline{F}_E$$

Motion Objective:

$$\underline{u} = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \rightarrow \begin{bmatrix} x_{end-effector} \\ y_{end-effector} \end{bmatrix}$$

Task Impedence Control Law (Simultaneous Motion/Force Control):

$$\underline{u} = \ddot{\underline{x}}_d + k_v\dot{\underline{e}} + k_p\underline{e} + k_f(\underline{F}_d - \underline{F}_E)$$

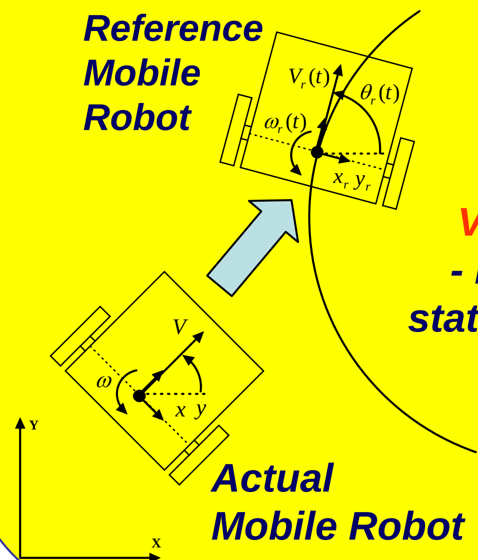
Stable Error Dynamics:

$$\ddot{\underline{e}} + k_v\dot{\underline{e}} + k_p\underline{e} = k_f(\underline{F}_d - \underline{F}_E)$$

Null-(Internal) Space Control

[Secondary Control Space]

- **Internal redundant control that secondarily attempts to achieve mobile base tracking of a reference trajectory.**

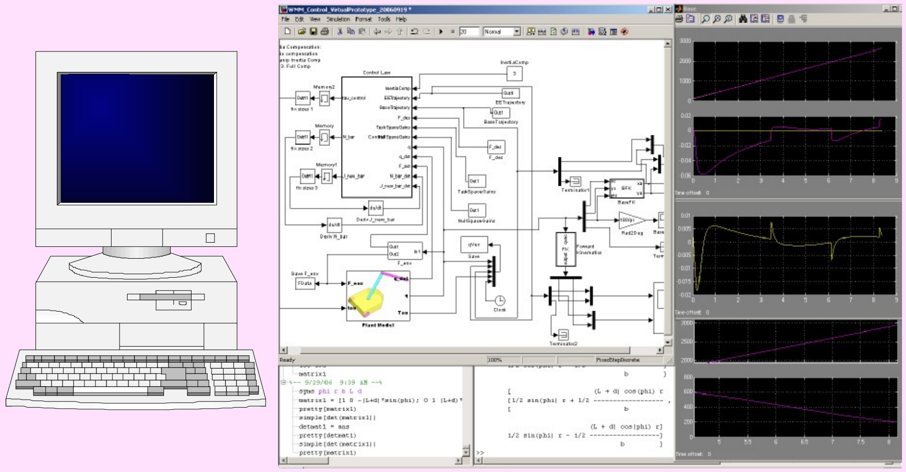


$$\underline{v} = \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} \rightarrow \begin{bmatrix} \theta_R{}^d \\ \theta_L{}^d \end{bmatrix}$$

Virtual Robot Algorithm

- Nonlinear time-varying state feedback control law for point stabilization

Integrated Software Framework



Distributed Virtual Prototyping

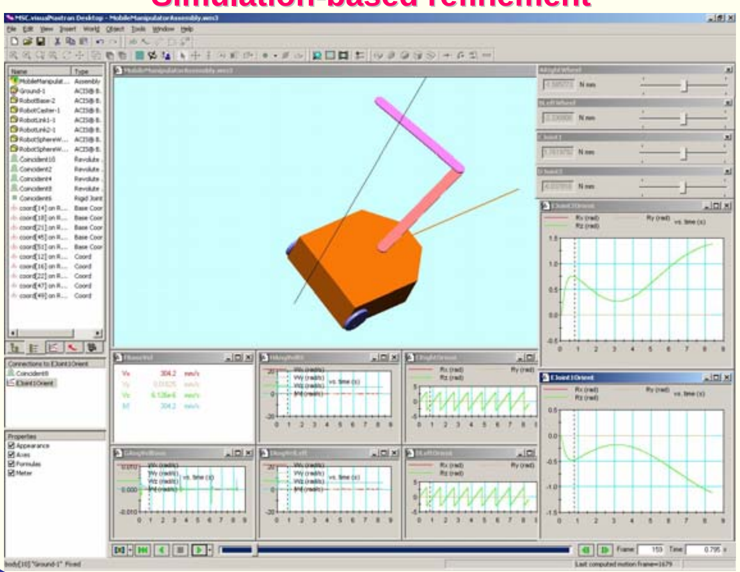
Ethernet/TCPIP

Remote Distributed Control

Ethernet/TCPIP

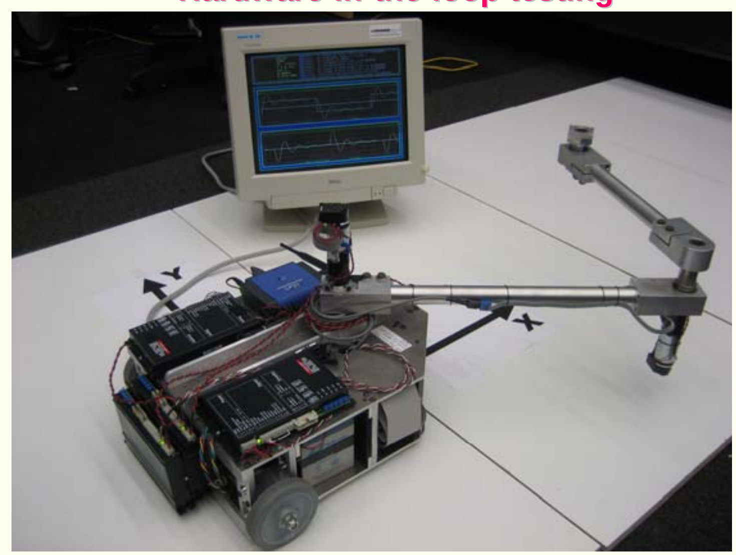
Virtual Prototype

Simulation-based refinement

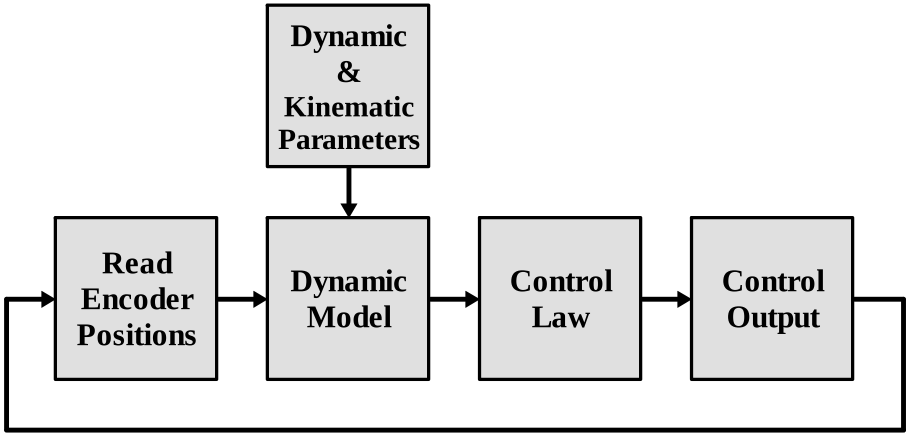


Physical Prototype

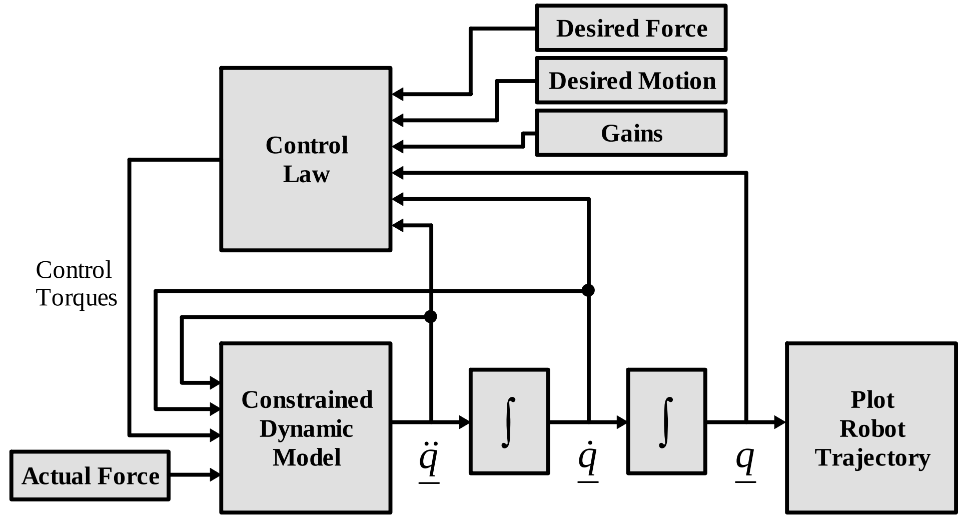
Hardware-in-the-loop testing



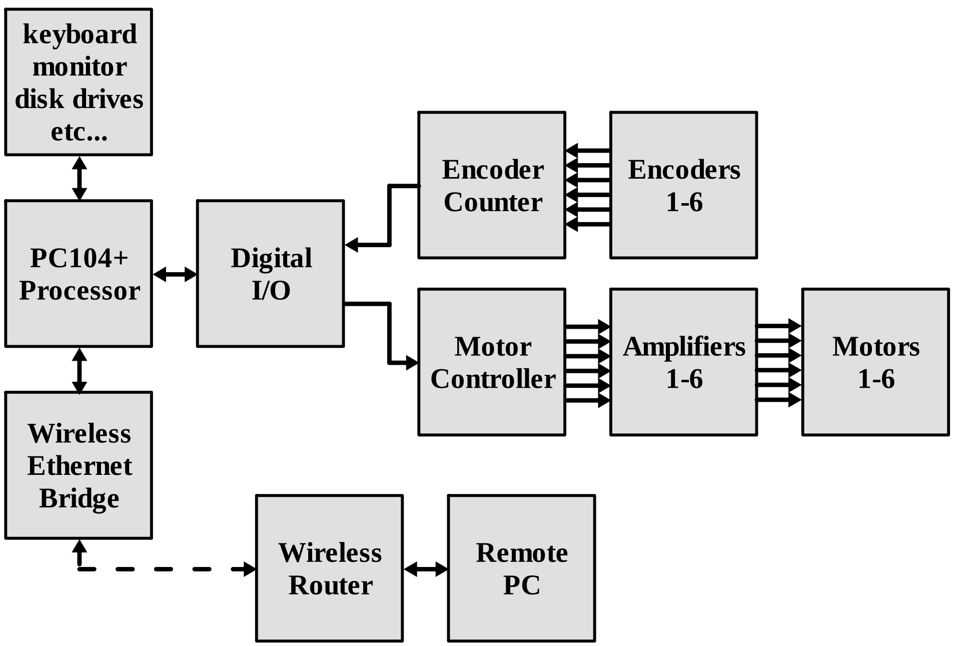
Implementation Framework



High Level System Implementation



Software/Control Algorithm Implementation (MATLAB/Simulink)

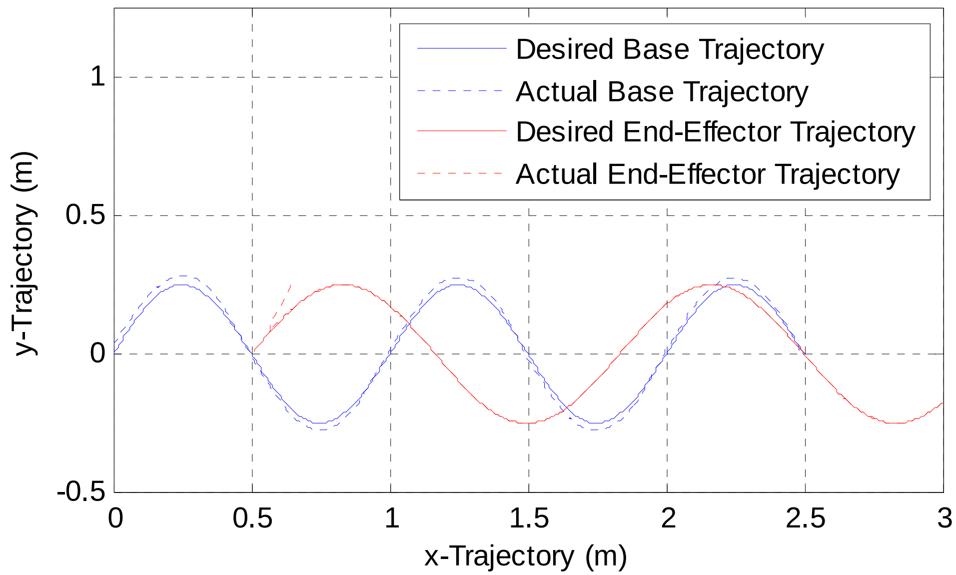


PC/104-Based Electronics Hardware Implementation

Simulation I: Motion / Trajectory Tracking

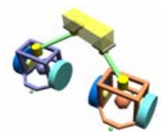
End-effector and mobile base follow separate sinusoids

No interaction force control



Movie

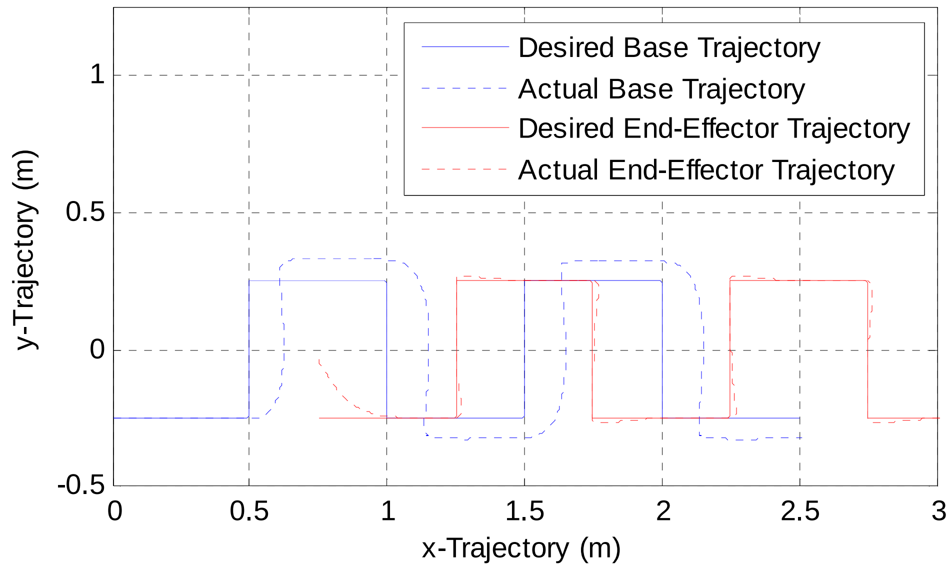
- **Initial errors at both end-effector and mobile base are corrected.**
- **There are no conflicting control objectives. Both end-effector and mobile base track the desired trajectory closely.**



Simulation II: Motion / Trajectory Tracking

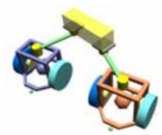
End-effector and mobile base follow separate square waves

No interaction force control



Movie

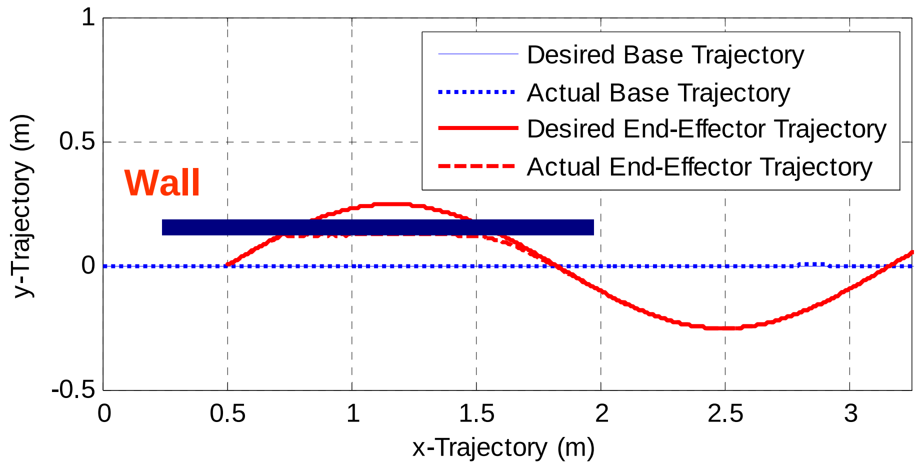
- **Initial errors at the end-effector is corrected.**
- **The control objectives of the end-effector and mobile base are conflicting during operation. End-effector tracks the required trajectory closely, but mobile base attempts to track “approximately”.**



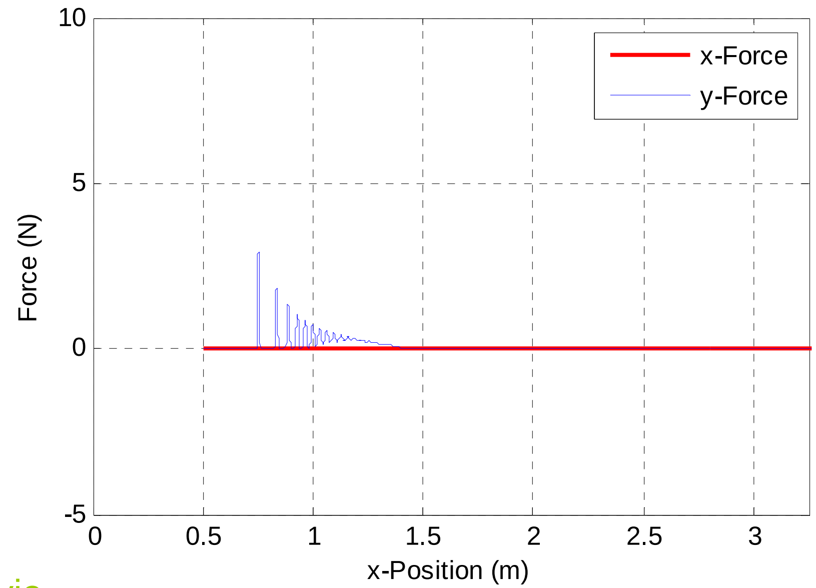
Simulation III: Simultaneous Motion / Interaction Force Tracking

End-effector follows sinusoids and applying desired (zero) force at a wall
Mobile base follow a straight line trajectory

Trajectory



Force

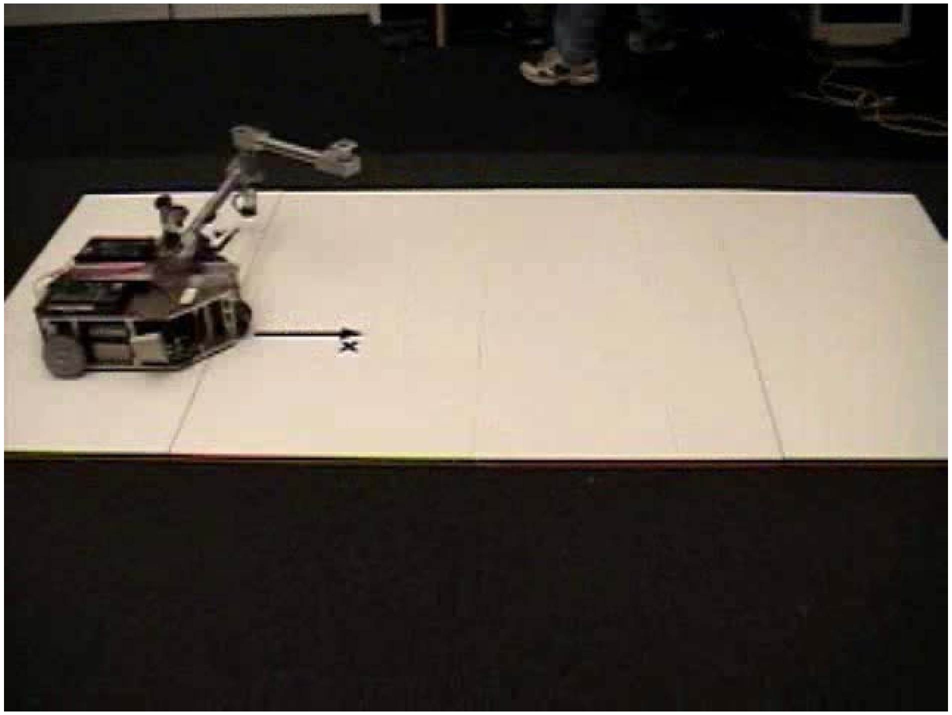


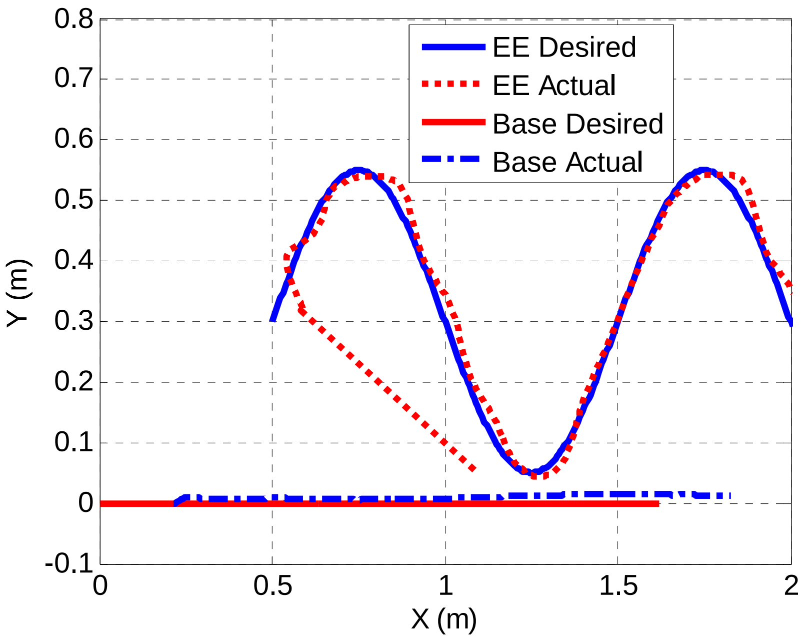
Movie

– **When the end-effector hits the wall, the system attempt to apply the desired (constant/zero) force at the wall.**

Experimental Result I: Motion / Trajectory Tracking

End-effector tracks sinusoidal trajectory
Mobile base tracks a straight line
No interaction force control

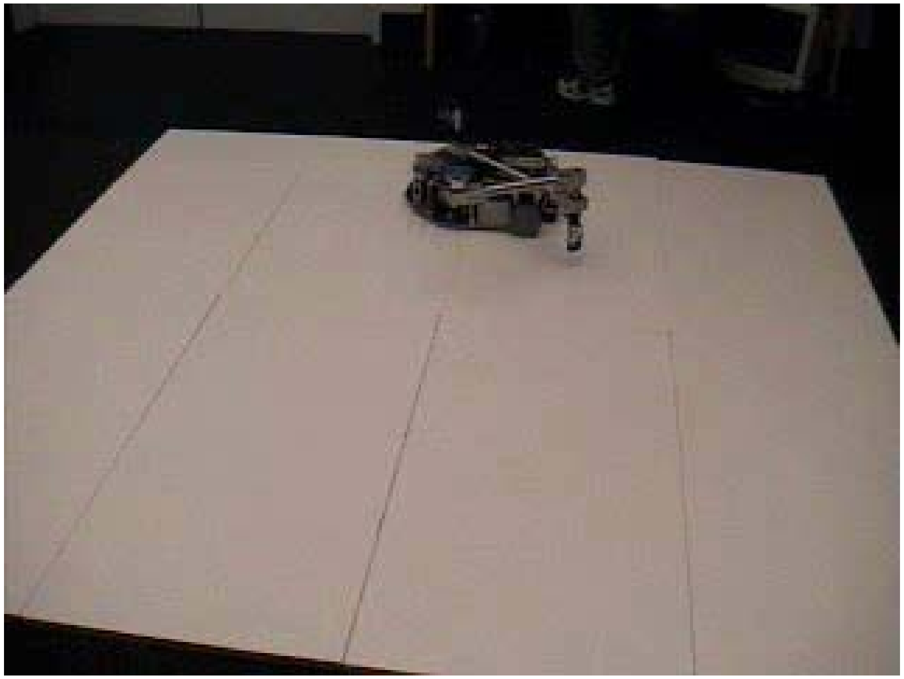


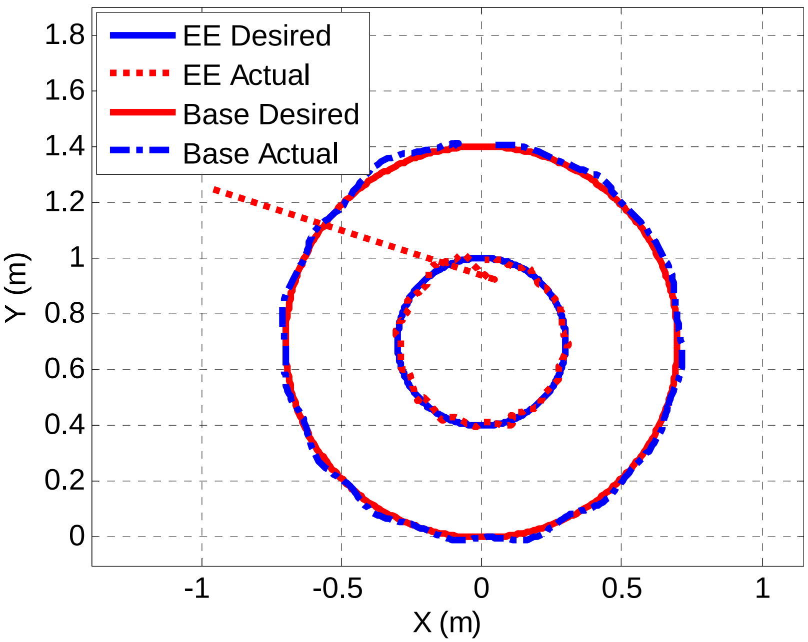


Experimental Result II: Motion / Trajectory Tracking

End-effector and mobile base tracks different circular trajectory

No interaction force control





Discussion

– Verified the capability of the developed control framework to *resolve redundancy* and permit creation of a *decoupled end-effector impedance-mode controller*

– Demonstrated the ability to exploit the redundancy to *simultaneously follow complex end-effector* and *secondarily follow mobile base paths* (with a natural prioritization to end-effector tracking performance)

– Established the required *infrastructure* and *decouple dynamic control framework* to achieve decentralized payload manipulation by multiple mobile manipulator agents

Thank You!