Dynamic Redundancy Resolution and Decoupled Control of a Nonholonomic Wheeled Mobile Manipulator

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Introduction

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

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

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***

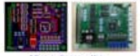
Mechanical Prototype Realization

Control:

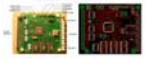
- ***Redundancy resolution schemes (kinematic/dynamics)***
- ***Disturbance compensation/rejection***

Validation:

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



Motor Controller



Encoder Coprocessor

Redundancy Resolution Algorithms

Challenges

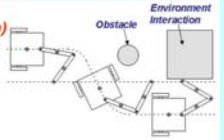
- ***Nonholonomic constraints*** due to wheel assemblies.
- Combining mobility of the wheeled platform and mounted manipulator creates both ***kinematic and actuator/dynamic redundancy***.

Methods

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

...such that:

- the ***primary (end-effector motion)*** and ***secondary (internal motion) objectives*** can be achieved independently in a ***dynamically consistent sense***
- while taking into account of ***nonholonomic constraints.***



Illustrations

Dynamic Modeling

Constrained Dynamic Equation

with extended generalized coordinates

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

$$\underline{q} = \left[x,\ y,\ \phi,\ \theta_R,\ \theta_L,\ \theta_1,\ \theta_2\right]^T$$

Nonholonomic Constraints

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

$$S^T \xrightarrow{\text{Projection}} S^TA^T = 0$$

Feasible Dynamic Equation

with minimal generalized coordinates

$$S^TMS\dot{\underline{\nu}} + S^TM\dot{S}\underline{\nu} + S^TV = S^TE\underline{\tau}_m + S^TE_2\underline{F}$$

$$\underline{\nu} = \left[\dot\theta_R\ \ \dot\theta_L\ \ \dot\theta_1\ \ \dot\theta_2\right]^T$$

Simplified Dynamic Equation:

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

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

External (End-Effector) Forces

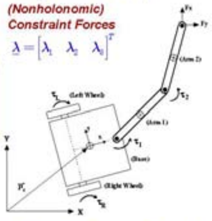
$$\underline{F} = \left[F_x\ \ F_y\right]^T$$

Joint Actuations

$$\underline{\tau}_m = \left[\tau_R\ \ \tau_L\ \ \tau_1\ \ \tau_2\right]^T$$

(Nonholonomic) Constraint Forces

$$\underline{\lambda} = \left[\lambda_1\ \ \lambda_2\ \ \lambda_3\right]^T$$



Dynamic Redundancy Resolution

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

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

Kinematic Redundancy Resolution Schemes

Velocity (rate) level $\dot{\underline{z}} = J^{\#}\dot{\underline{x}} + N\dot{\underline{z}}_0$

Acceleration level $\ddot{\underline{z}} = J^{\#}(\ddot{\underline{x}} - \dot{J}\dot{\underline{z}}) + N\ddot{\underline{z}}_0$

Special Case: Take "Dynamically Consistent Pseudoinverse"

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

Decoupled (Minimal) Joint Space Dynamics:

$$J^T\underline{F} + N^T\underline{\tau} = \underbrace{J^T\bar{J}^T\left(HJ\left(\ddot{\underline{z}} - \dot{J}\dot{\underline{z}}\right) + C\dot{\underline{z}} + g - \underline{\tau}_E\right)}_{\text{Task Dynamic}} + \underbrace{N^T\left(HN\left(\ddot{\underline{z}}\right) + C\dot{\underline{z}} + g - \underline{\tau}_E\right)}_{\text{Null (Internal) Dynamic}} + \underbrace{\overbrace{J^T\bar{J}^THN\ddot{\underline{z}} + \bar{N}^THJ\left(\ddot{\underline{z}} - \dot{J}\dot{\underline{z}}\right)}^{0}}_{\text{Coupling}}$$

Total Input Torque:

$$\underline{\tau} = \underbrace{J^TW(\underline{u} - \dot{J}\dot{\underline{z}})}_{\text{Task Space Control}} + \underbrace{\bar{N}^TH(\underline{v} + \dot{\bar{J}}\dot{\underline{x}})}_{\text{Null (Internal) Space Control}} + C\dot{\underline{z}} + \underline{g} + J^T\underline{F}_E$$

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:

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

Motion Objective:

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

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

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

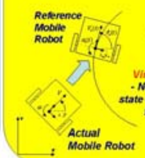
Stable Error Dynamics:

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

Null-(Internal) Space Control

[Secondary Control Space]

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

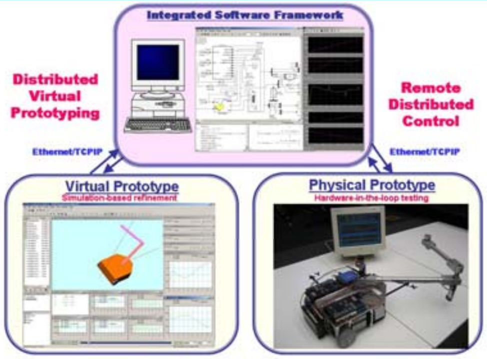


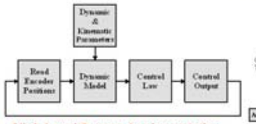
$$\underline{v} = \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} \to \begin{bmatrix} \theta_R^d \\ \theta_L^d \end{bmatrix}$$

Virtual Robot Algorithm

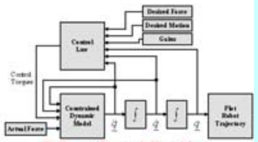
- Nonlinear time-varying state feedback control law for point stabilization

Implementation Framework

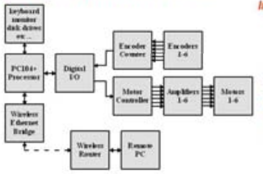




High Level System Implementation



Software/Control Algorithm Implementation (MATLAB/Simulink)



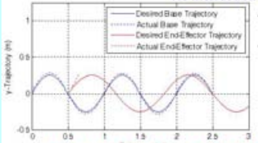
PC/104-Based Electronics Hardware Implementation

Results

Motion / Trajectory Tracking

End-effector and mobile base follow separate sinusoids

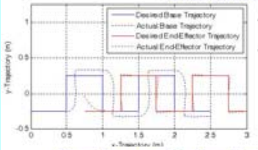
No interaction force control



- 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.

End-effector and mobile base follow separate square waves

No interaction force control

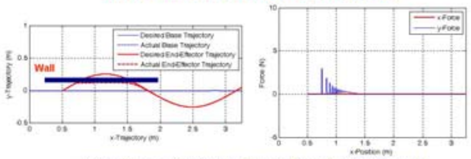


- Initial errors at the end-effector is corrected.
- The control objectives of the end-effector and mobile base are conflicting during operation. End-effector tracks the required trajectory closely, but mobile base attempts to track "approximately".

Simultaneous Motion / Interaction Force Tracking

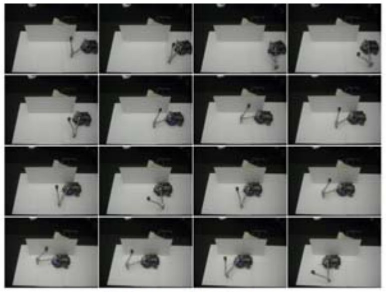
End-effector follows sinusoids and applying desired (zero) force at a wall

Mobile base follow a straight line trajectory



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

Movie Demonstration of an Example of Simultaneous Force/Motion Control



Conclusion

- 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)

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