Planning and Control of Space Robotic Systems on Orbit

Evangelos Papadopoulos and Ioannis Tortopidis

Control Systems Laboratory
Department of Mechanical Engineering
National Technical University of Athens

Motivation

- Space (on-orbit tasks)
  - Hazardous or physically impossible
  - Very costly safety support systems
- A solution: Space robots
- Unique Problems
  - No fixed-base
  - Base-manipulator coupling

Free-floating Space Robots - 1

- Satellite with one or more manipulators
- Free-floating => Base thrusters do not operate.
- A space robot with an N-dof manipulator has N+6 dof.
- N manipulator dof are actuated.
- Underactuated system.
- Kinematics and dynamics reduced to N equations using *momentum* equations.

Free-floating Space Robots - 2

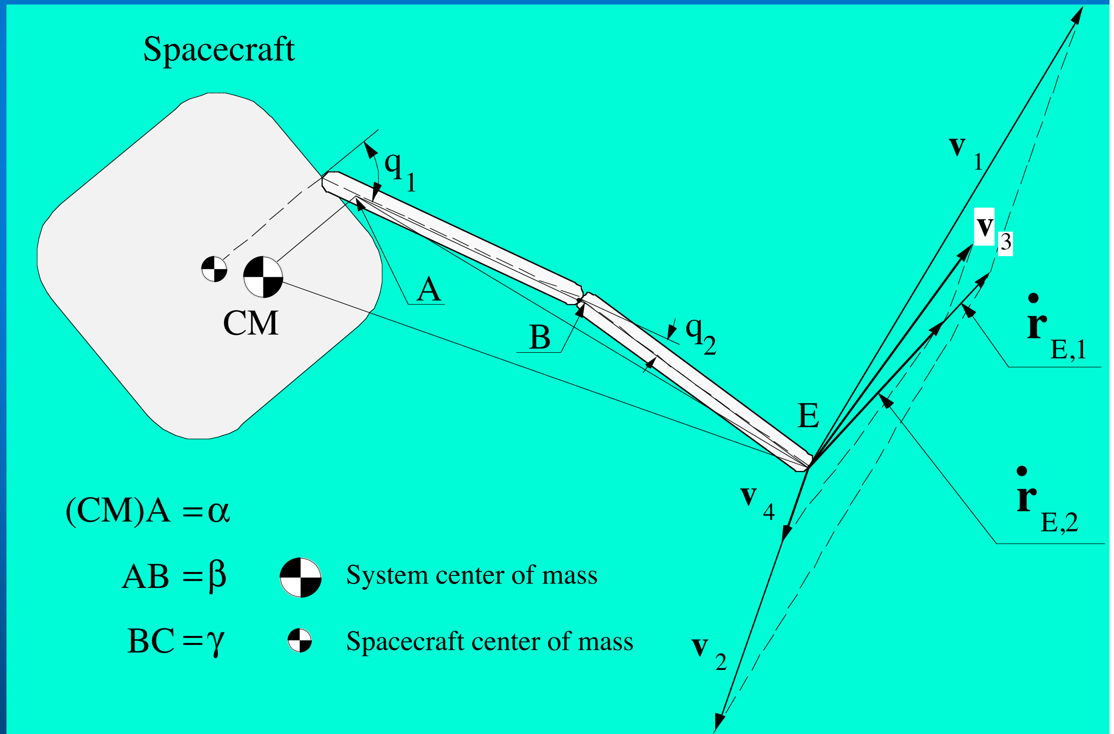
- Use reduced kinematics and dynamics (N dof)
- Non-integrable angular momentum conservation must be appended
- Nonlonomic behavior:
  Spacecraft attitude = *f*(manipulator joint-space path)

Free-floating Robots Planning

- Can we control a spacecraft's attitude & end-effector position using manipulator motions only?
  - Hard question
  - Astronauts, cats
  - Joint space motions
  - Cartesian space motions & dynamic singularities

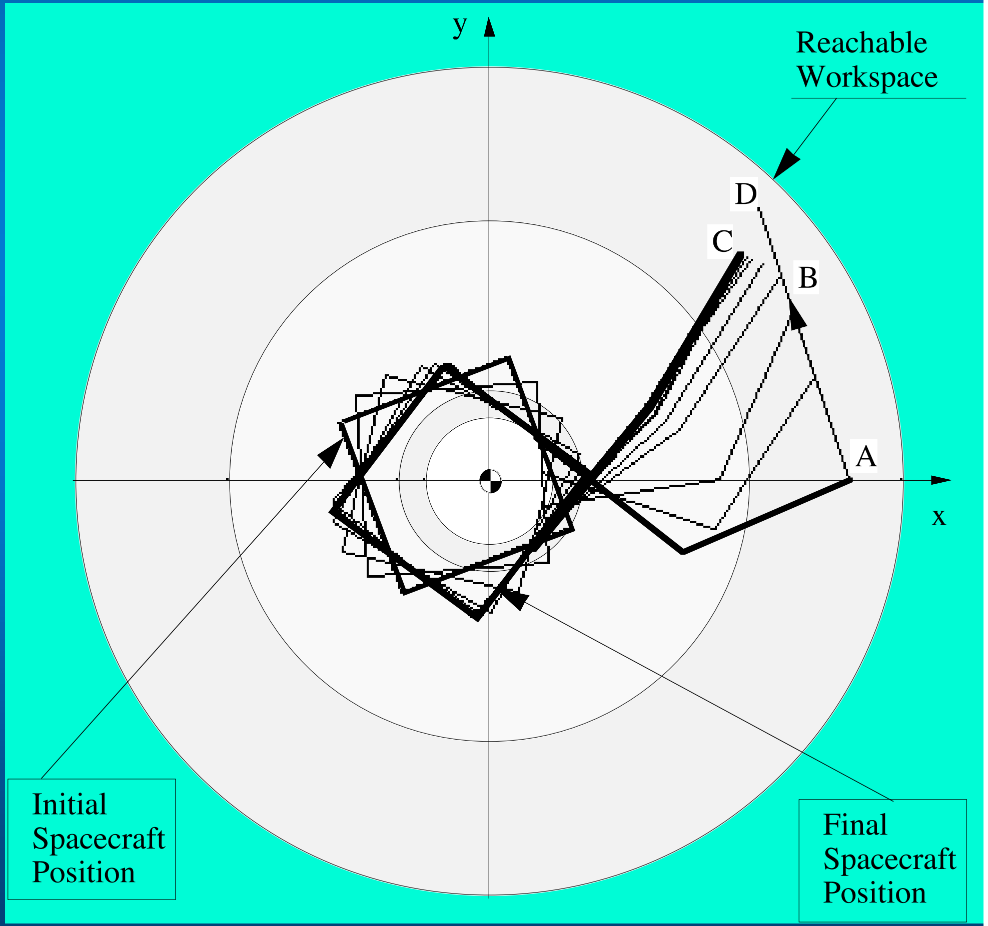
Dynamic Singularities - 1

- At a dynamic singularity (shown here)
  - Base motion counteracts end-effector motion
  - Motion dofs are lost
  - Cartesian location singularity is path dependent
  - All control algorithms fail there.



Dynamic Singularities - 2

- Move from A to D on a straight line
  - Use a Transpose Jacobian algorithm
  - End-effector moves up to point B
  - At B, a dynamic singularity occurs
  - End-effector moves to point C
  - Cannot recover (Null space)
  - Other algorithms would fail there.

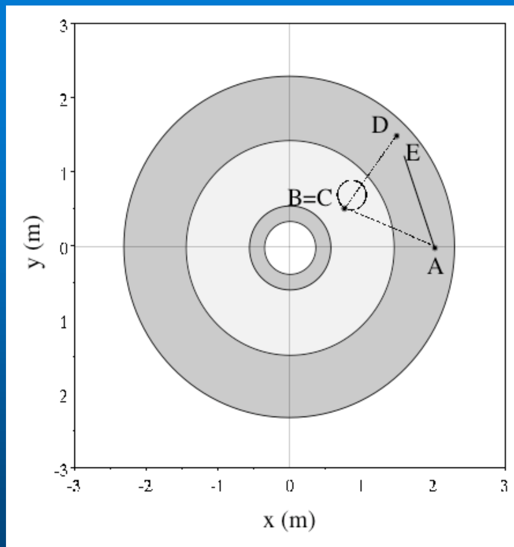


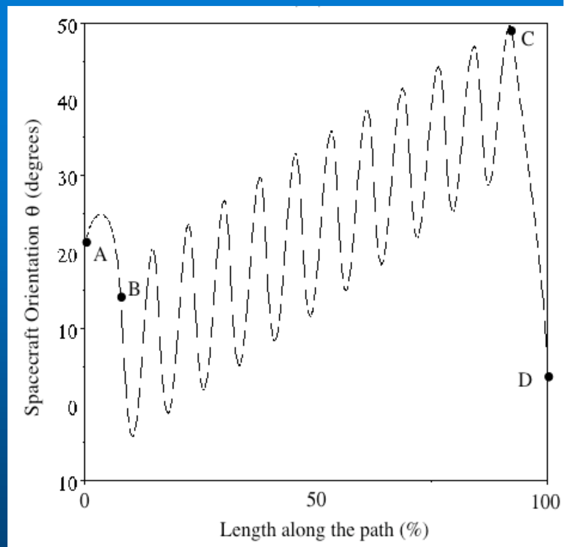
Point to Point Control: Early Solution

- Find a simple path, if any, that will take the end-effector to a desired point, avoiding dynamic singularities

Cyclical Motions

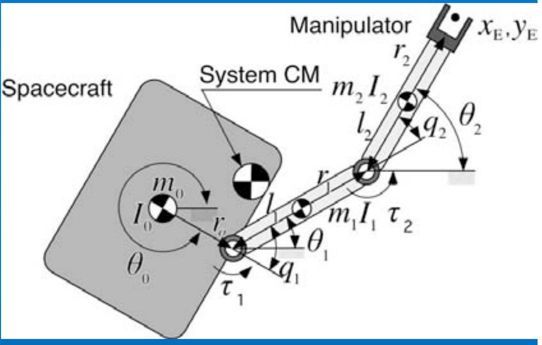
- A->C in PIW, record attitude
- D->C in PIW, record attitude
- Small cyclical motions to match attitudes (Lie)
- Inexact computation for number of required cycles
- Time consuming & not straightforward





Problem Statement

- Find a simple path, if any, that will take the space robot to a desired configuration
  - in prescribed time,
  - without small cyclical motions,
  - with smooth trajectories, torques,
  - using the actuated manipulator only.



Methodology Outline

- The key idea is to use high order polynomials as *arguments* in cosines.
- The initial problem is converted to one of satisfying the motion integrals.
- The configuration accessibility is *drastically extended.*
- Free parameters are determined by optimization techniques.
- At least one path can be obtained, provided that the desired change in configuration lies between physically permissible limits.

Attitude Permissible Bounds

- A change in manipulator configuration causes a bounded change in base attitude $\Delta\theta_0$

$$d\theta_0 = -\frac{(D_1 + D_2)}{D} dq_1 - \frac{D_2}{D} dq_2 \triangleq g_1(\mathbf{q})dq_1 + g_2(\mathbf{q})dq_2$$

$$\Delta\theta_0 = \int g_1(\mathbf{q})dq_1 + \int g_2(\mathbf{q})dq_2 \triangleq \Delta\theta_{01} + \Delta\theta_{02}$$

where g_1, g_2 are bounded functions of $\mathbf{q}$.

- Bounds for base attitude change are computed

$$\Delta\theta_{0,\min} < \Delta\theta_0 < \Delta\theta_{0,\max}$$

- If $\Delta\theta_0$ outside the computed range, *no path* exists.

Kinematics - 1

- Base attitude described using ZYX Euler angles (Yaw-Pitch-Roll)

$$\psi_0 = [\theta_1 \quad \theta_2 \quad \theta_2]^T$$

- Euler Angle rates and angular velocity

$$\dot{\psi}_0 = \mathbf{E}^{-1}(\psi_0)\,{}^0\boldsymbol{\omega}_\mathbf{0} = \frac{1}{c_2}\begin{bmatrix} 0 & s_3 & c_3 \\ 0 & c_2c_3 & -c_2s_3 \\ c_2 & s_2s_3 & s_2c_3 \end{bmatrix} {}^0\boldsymbol{\omega}_\mathbf{0}$$

$$\mathbf{q}$$

- Manipulator configuration

Kinematics - 2

- End-effector location/orientation a function of base attitude and $\mathbf{q}$
- Cartesian and joint space problem are now equivalent
- Joint space planning NOT subject to dynamic singularities!
- Therefore, plan in joint space.

Dynamics

- Zero external forces and moments
- N Equations of motion

$$\mathbf{H}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}}) = \boldsymbol{\tau}$$

- Angular momentum

$${}^{0}\boldsymbol{\omega}_{0} = \underbrace{-{}^{0}\mathbf{D}^{-1}(\mathbf{q})\,{}^{0}\mathbf{D}_{\mathbf{q}}(\mathbf{q})}_{\mathbf{F}_1(\mathbf{q})}\dot{\mathbf{q}}$$

Nonholonomic Planning - 1

- Angular momentum (rewritten) $\dot{\psi}_0 = \mathbf{E}^{-1}(\psi_0)\mathbf{F}_1(\mathbf{q})\dot{\mathbf{q}}$
- Path = ?: $(\psi_0^{in}, \mathbf{q}^{in}) \Rightarrow (\psi_0^{fin}, \mathbf{q}^{fin})$
  by actuating manipulator joints only.
- Let: $q_i = q_i(t, \mathbf{b}_i), \quad \mathbf{b}_i \; ((k_i + 1) \times 1), \quad i = 1, \cdots, N$
  polynomials of order k_i
- Free parameters: $n_f = (k_1 + k_2 + \cdots + k_N + N)$
  (for N-dof manipulator)

Nonholonomic Planning - 2

- Min #Constraints: $n_c \geq 6N + 3$
  - Six per joint (for initial – final position, and zero initial – final velocities & accelerations)
  - Plus at least three, for the integrals of motion (the angular momentum conservation equation in three axes)

- Since it must be: $n_f \geq n_c$ we have

$$(k_1 + k_2 + \cdots + k_N) \geq 5N + 3$$

$$k_i \geq 5, (i = 1, \ldots, N)$$

Nonholonomic Planning - 3

- Let $\mathbf{b} \in \mathbb{R}^k$ the vector containing the remaining free parameters for all $\mathbf{b}_i \ (i = 1, \cdots, N)$, after boundary conditions for all joints are satisfied.
- Then we can write $\mathbf{q} = \mathbf{q}(t, \mathbf{b})$ and $\dot{\boldsymbol{\psi}}_0 = \mathbf{F}(\boldsymbol{\psi}_0, \mathbf{b}, t)$
- Free parameters should be at least three, i.e. $(k \geq 3)$ and satisfy the integrals of motion, i.e.

$$\boldsymbol{\psi}_0^{fin}(\mathbf{b}) = \boldsymbol{\psi}_0^{fin}(des), \ or$$

$$\mathbf{h}(\mathbf{b}) \triangleq \boldsymbol{\psi}_0^{fin}(\mathbf{b}) - \boldsymbol{\psi}_0^{fin}(des) = \mathbf{0}$$

  – The problem reduces to determining the unknown vector $\mathbf{b}$, numerically.

Nonholonomic Planning - 4

- If $k \geq 3$ the vector **b,** is determined using optimization techniques, as

$$\left\|\mathbf{b}\right\| \rightarrow \min : \mathbf{h}(\mathbf{b}) = \mathbf{0}$$

- Even for $k = 3$ the problem may have multiple solutions (i.e. paths achieving the double goal).

- Approach always yields a path, if the desired change in attitude lies between physically permissible bounds.

Discussion on Planning - 1

- We are mostly interested in finding solution(s) satisfying the equality constraints, rather than finding the global minimum for $\mathbf{b}$.

- Additional requirements, i.e.
  - Attitude change maximization
  - Joint limits
  - Obstacle avoidance

  can be achieved, by adding more freedom to the end-point path, via the use of higher order polynomials for one or more joints.

Discussion on Planning - 2

- With joint-space trajectories determined, the base attitude is given by integrating $\dot{\psi}_0 = \mathbf{F}(\psi_0, \mathbf{b}, t)$
- Initial and final velocities and accelerations of ψ_0 are necessarily zero
- Since the path is defined directly in the joint space, it is always feasible and will never be subject to Dynamic Singularities problems

Planar Example

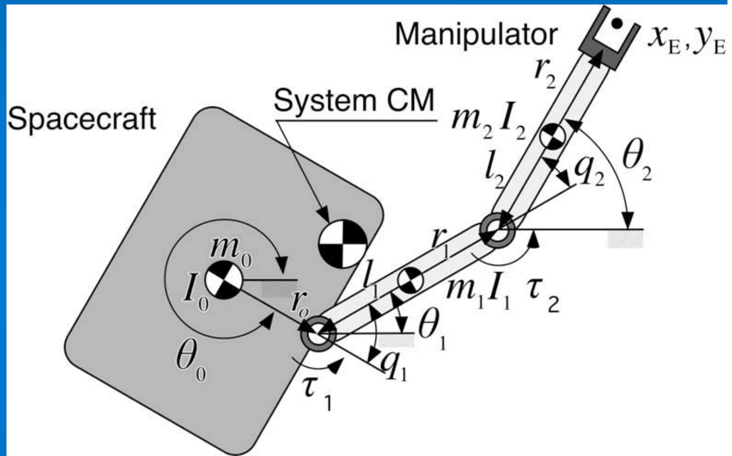
- Angular momentum

$$D_0(\mathbf{q})\,d\theta_0 + D_1(\mathbf{q})d\theta_1 + D_2(\mathbf{q})\,d\theta_2 = 0$$

- End-point location

$$x_E = a\cos\theta_0 + b\cos\theta_1 + c\cos\theta_2$$

$$y_E = a\sin\theta_0 + b\sin\theta_1 + c\sin\theta_2$$



- System parameters

Body	l_i (m)	r_i (m)	m_i (Kg)	I_i (Kg.m^2)
0	1.0	0.5	400	66.667
1	0.5	0.5	40	3.33
2	0.5	0.5	30	2.5

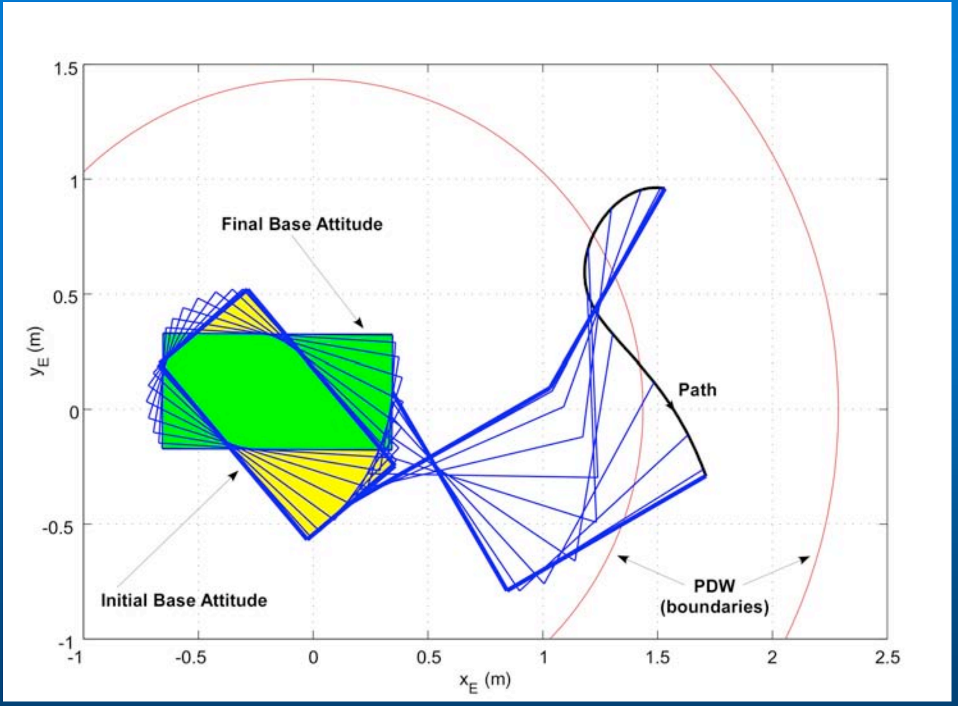
2D: New System Configuration - 1

$$(\theta_0, x_E, y_E)^{in} = (-50^o, 1.53m, 0.96m) \xrightarrow{desired} (\theta_0, x_E, y_E)^{fin} = (0^o, 1.71m, -0.29m)$$

$$(\Delta q_1, \Delta q_2) = (-140.0^o, 60.0^o),\ \Delta\theta_0 \in (1.4^o, 72.2^0)$$

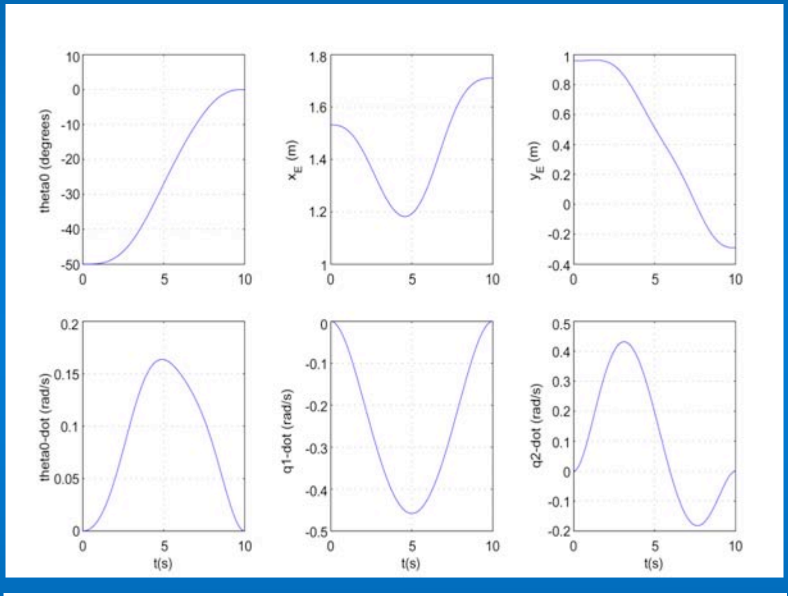
$$\Delta\theta_0^{des} = 50^o:\ k_1 = 5,\ k_2 = 6 \Rightarrow Infinite\ \ solutions\ \ for\ \ b_{26}(free).t = 10s.$$

- Using optimization, minimum b_{26} is defined, yielding the shortest path, as shown

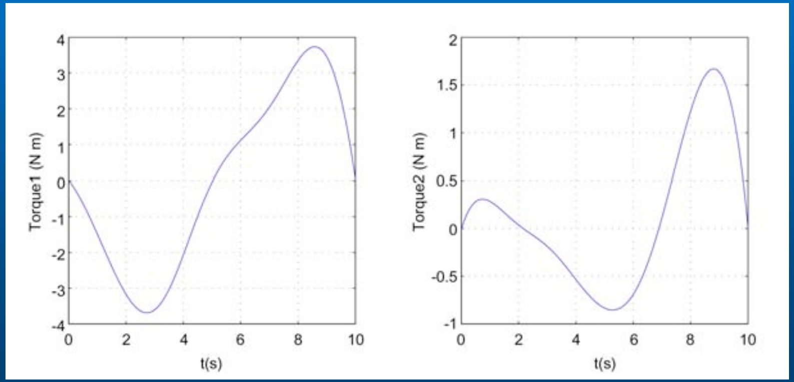


2D: New System Configuration - 2

- Configuration history

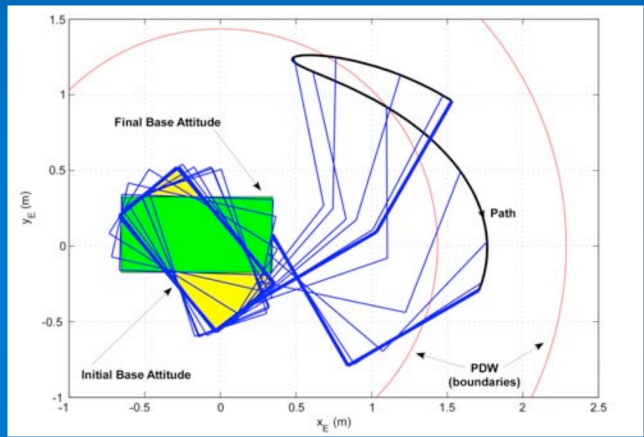


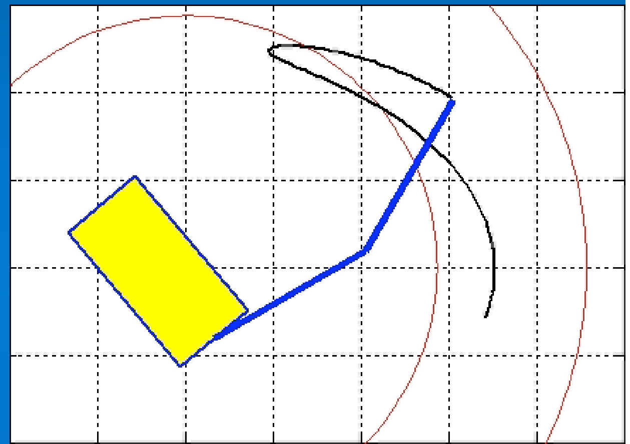
- Actuator torques



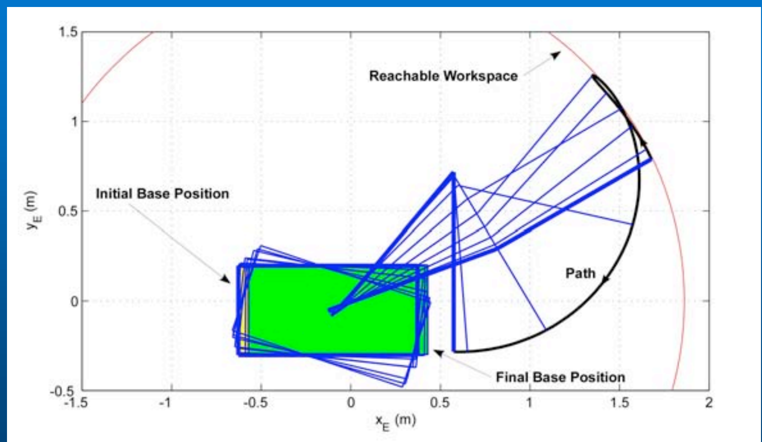
Planning & Control

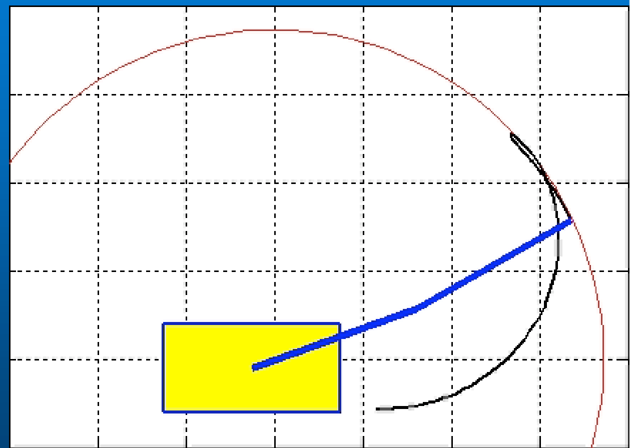
- Moving to a new prescribed configuration with two controls





- Moving to a new point, keeping the orientation constant





Spatial Example

- Base has 6-dof
- 3D manipulator has 3 actuated links (3 dof)
- Total 9 dof

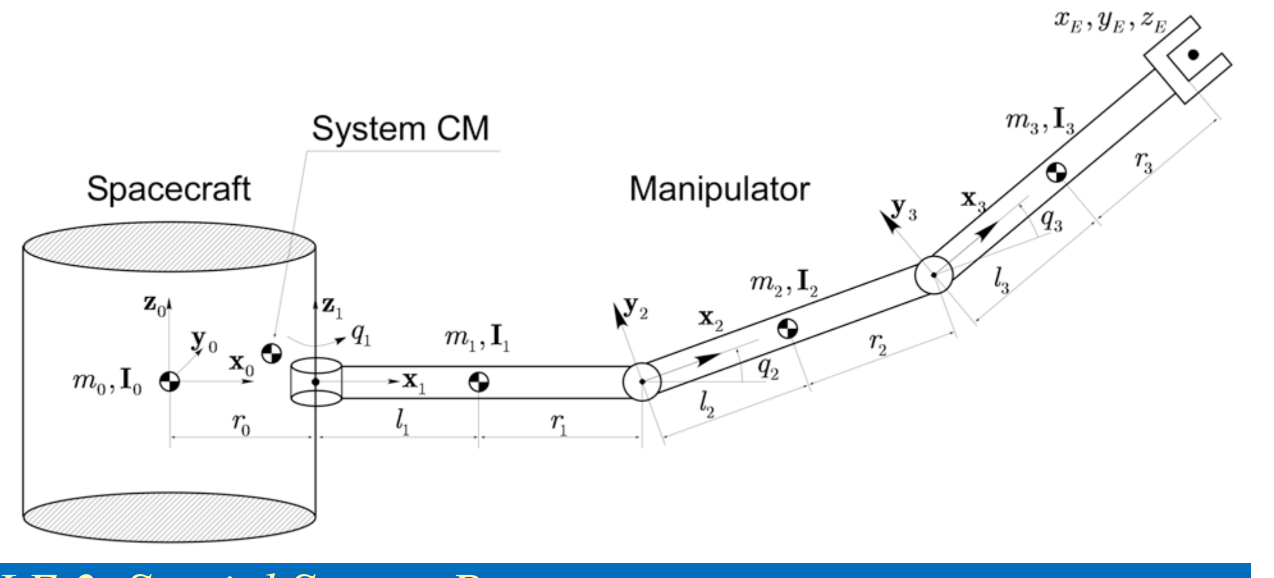


TABLE 2. Spatial System Parameters

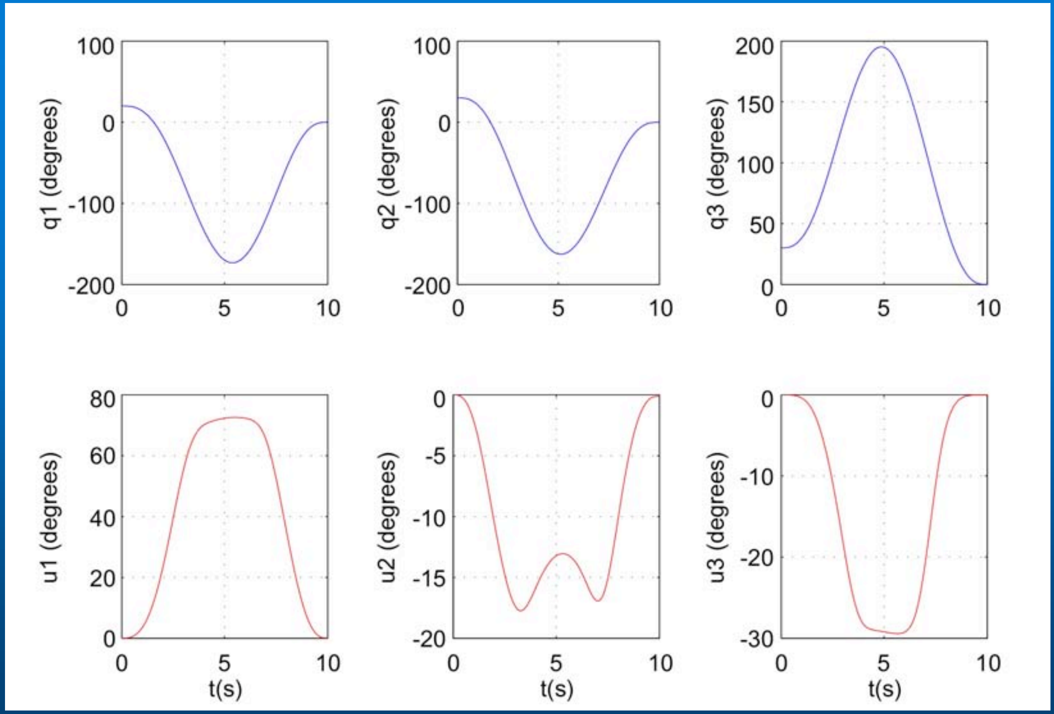
Body	l_i $[m]$	r_i $[m]$	m_i $[kg]$	I_{xx}, I_{yy}, I_{zz} $[kgm^2]$
0	0.5	0.5	400.0	66.7, 66.7, 66.7
1	0.5	0.5	30.0	0, 2.5, 2.5
2	0.5	0.5	30.0	0, 2.5, 2.5
3	0.5	0.5	20.0	0, 1.7, 1.7

3D: New Endpoint, Same Attitude

$$\psi_0^{fin} = \psi_0^{in}$$

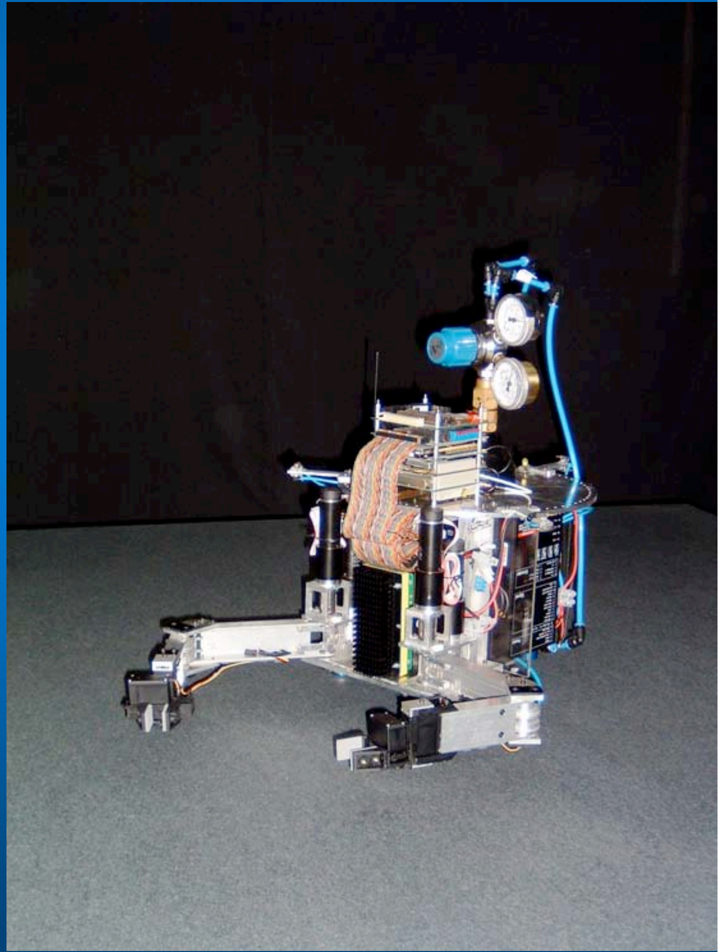
$$(q_1, q_2, q_3)^{in} = (20, 30, 30)^o \xrightarrow{desired} (q_1, q_2, q_3)^{fin} = (0, 0, 0)^o$$

Joint trajectories and resulting base attitude $(for\ k_1 = 7, k_2 = 6, k_3 = 6)$



Space Robot Simulator @ NTUA

- Robotic swarms, debris capture, assembly & maintenance tasks
- Two 2 dof manipulators
- 5 μm gap airbearing technology
- Thrust provided by PWM operated solenoid valves
- Fully autonomous, WiFi
- Optoelectronics, encoders, camera sensing
- QNX RTOS @ PC104 deck



Conclusions

- Developed point-to-point planning methods for controlling *both* base attitude and end-effector location
- The *key idea* is to use *high order polynomials* (as arguments in cosines), which drastically extend final configuration accessibility
- Optimization methods allow for easy determination of free parameters
- This approach leads always to a path, provided that the desired change in configuration lies between physically permissible limits
- System smoothly driven to desired configurations in prescribed time