Trajectory Planning for Robots: The Challenges of Industrial Considerations

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Introduction market, applications, and trends

- 1.5 million industrial robots in the world (2013, IFR)
  ; used in large industries (automotive, display)

Hyundai Motors, Czech Republic

LG Display, S. Korea

- Multi-purpose and efficient (6DOF, easy to program, fast with good repeatability)
  -> provides various applications (different from other automated machines)

- Trends: more intelligence (vision & force sensors), safety (collision, human-robot interaction)
  competitive market (cost reduction)
  → light weight design (less stiff)
  → the high motion performance is dependent on control methods (the main theme)

Purpose

- To introduce a typical motion planning method for industrial robots

- To review trajectory planning methods proposed in the literature
  (related to motion performance of industrial robots)

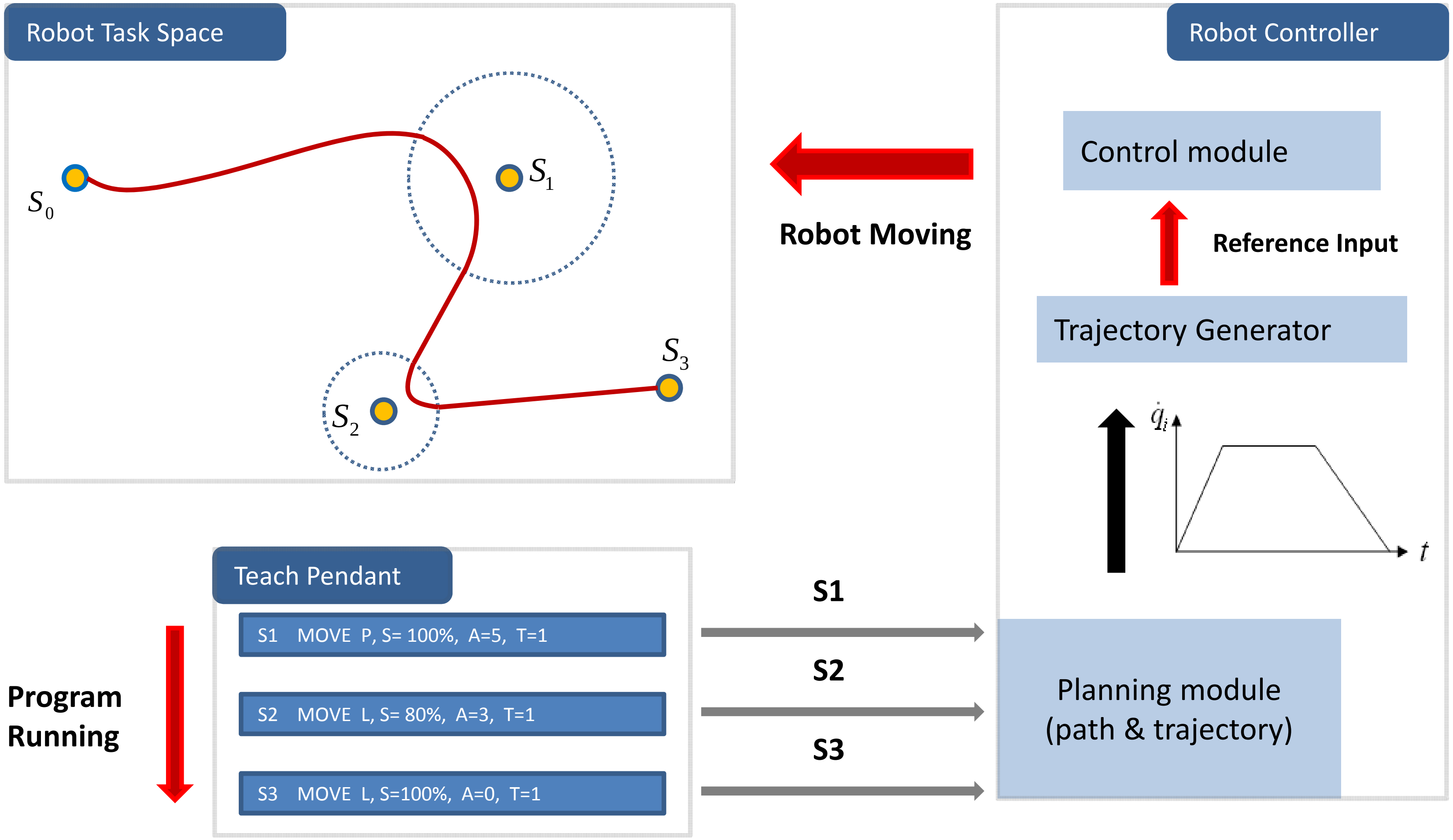
- To review some common but the most important constraints
  for generic industrial robot controllers

- To explain why some of well-known methods are not used in practice

Assumptions

- 6DOF industrial robots
- A generic robot controller (architecture, servo control loop)
- A good trajectory:
  ; simple (implementation, maintenance)
  ; efficient (small CPU burden)
  ; being able to address important constraints
  ; maximizes motion performance (high speed and high accuracy)

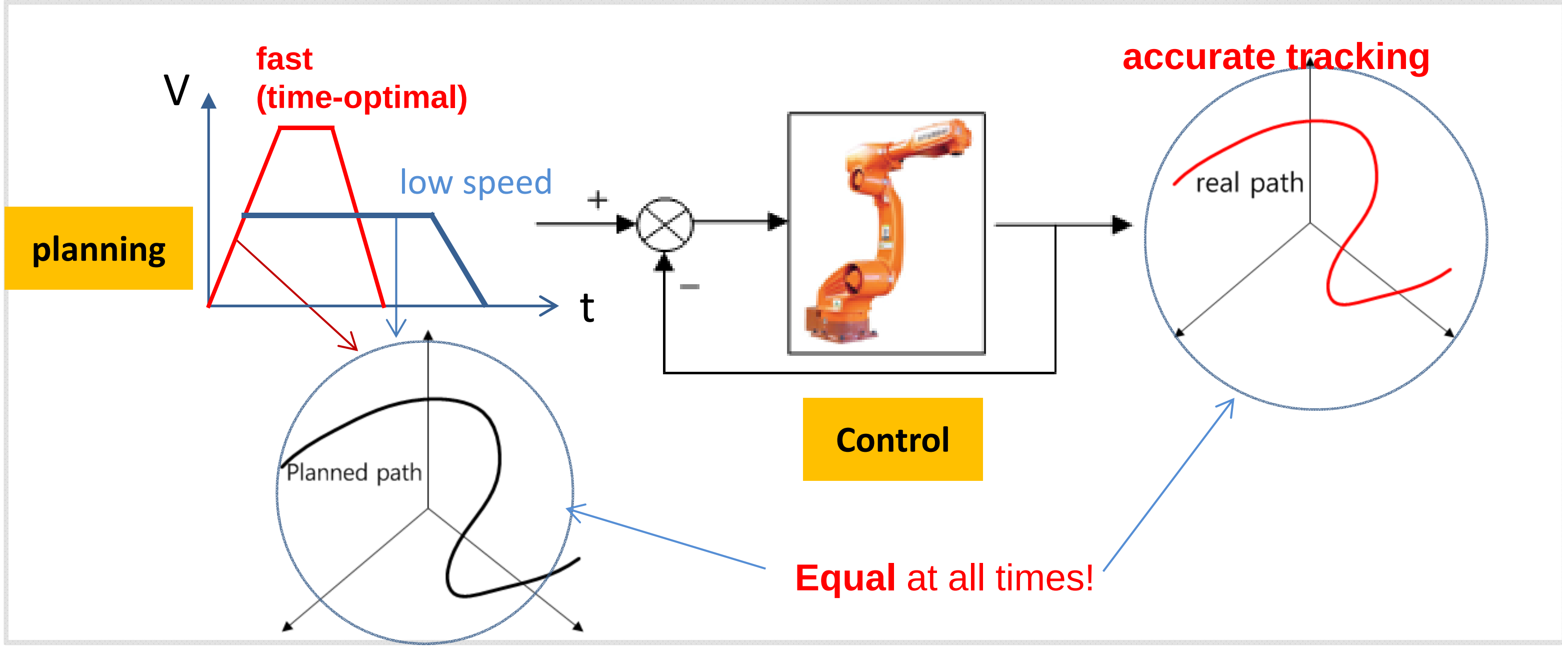
Introduction motion generation



HHI (Hyundai Heavy Industries Co.., Ltd.) robot system

Introduction An ideal motion control for industrial robots

Path-Invariant Time-Optimal Motion

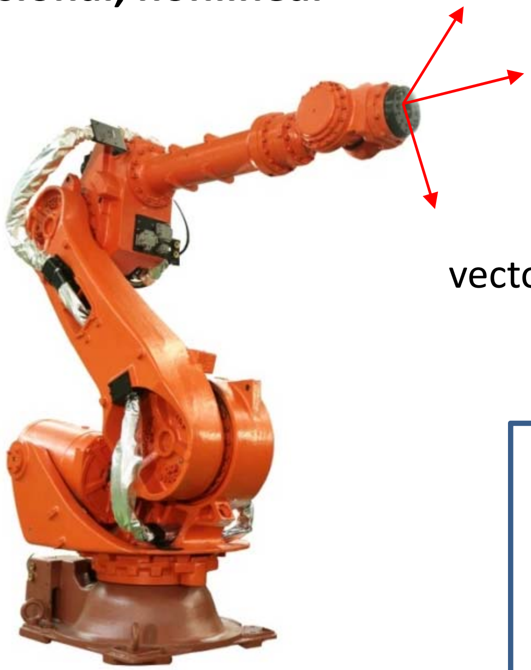


Requirements for trajectories

- *time-optimal*
- *generate a path independent of trajectories*
- *band-limited*

Challenges kinematics

Multi-dimensional, nonlinear

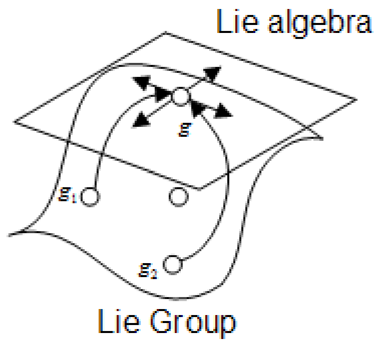


Task space

$\begin{bmatrix} \Re^3 & SO(3) \end{bmatrix}$

vector space

curved space (Lie Group)
(not a vector space)



joint space
$\Re^6$

HHI's HS165 (6DOF, payload: 165kg)

$\Re^n$ $\xrightarrow{f}$ $\begin{bmatrix} \Re^3 & SO(3) \end{bmatrix}$, f^{-1}

$$f : \Re^n \mapsto \left[\Re^3, SO(3) \right]$$

Multi-dimensional nonlinear map

- Need to address both positions and orientations
- Orientations: much more complex than positions

Kinematic constraints: path, maximum speed/acceleration/jerk

Challenges dynamics

Multi-dimensional, nonlinear, highly coupled

Equation of motion

$$\boldsymbol{\tau} = \mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{B}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{N}(\mathbf{q}) \in \Re^{12}$$

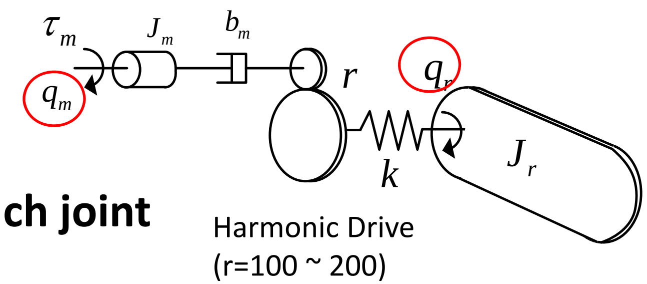
Inertia
- position-dependent
- coupled

Coriolis-Centrifugal and friction
- Pos. & vel. dependent
- coupled

Joint compliance, gravity
- position dependent
- coupled

Natural frequencies at steady-state: 3 ~ 25 Hz ($1 \sim 2^{nd}$ mode)
(very low, position dependent)

Joint (link) positions: not measurable!



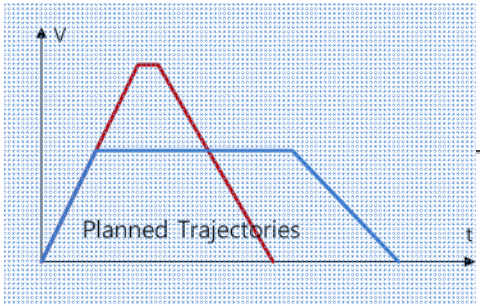
each joint

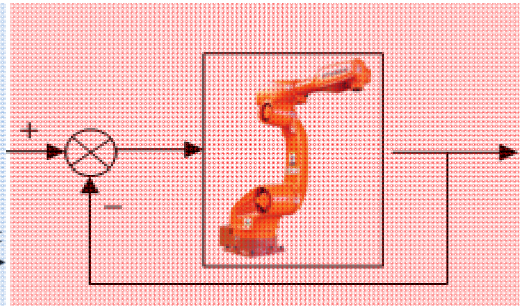
Constraints
- maximum torques (hard constraint)
- not exciting natural modes

Traditional Approach

Complex geometry + complex dynamics (too complicated)

→ Divide & Conquer (Planning / Control)





Planning Task (goals)

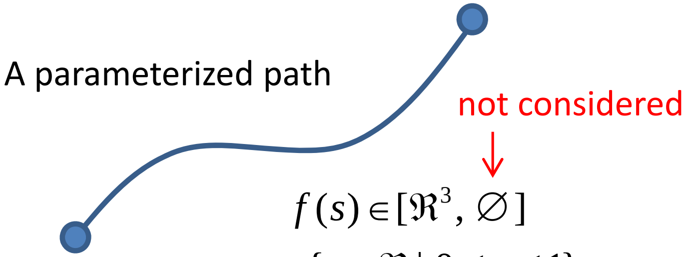
- **Increase speed**
  ; time-optimal trajectory planning
- **minimize vibrations**
  ; smooth motion trajectory planning

Control Task (goals)

- **Track accurately, respond quickly,**
- **Obtain stable motions**
  ; various control methods
  (linear, nonlinear, SISO, MIMO)

Well-Known Methods Time-optimal trajectories

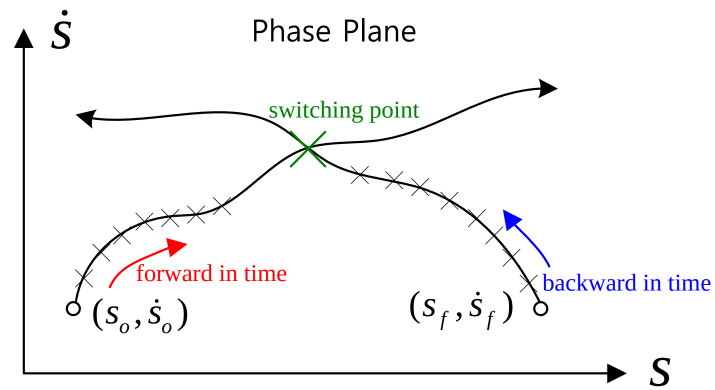
Time-Optimal Trajectory Planning



$$f(s) \in [\Re^3, \varnothing]$$

$$\{s \in \Re \mid 0 \le s \le 1\}$$

Find the time-optimal trajectory



EOM $\quad \boldsymbol{\tau} = \boldsymbol{m}(s)\ddot{s} + \boldsymbol{c}(s,\dot{s}) \in \Re^n$

Constraints

$$-\left|\boldsymbol{\tau}_{\max}\right| \le \boldsymbol{m}(s)\ddot{s} + \boldsymbol{c}(s,\dot{s}) \le \left|\boldsymbol{\tau}_{\max}\right|$$

$$\Rightarrow \quad \ddot{s}_{\max,acc} = \min\left[\frac{\left|\tau_{\max,i}\right| - c_i(s,\dot{s})}{m_i(s)}\right]$$

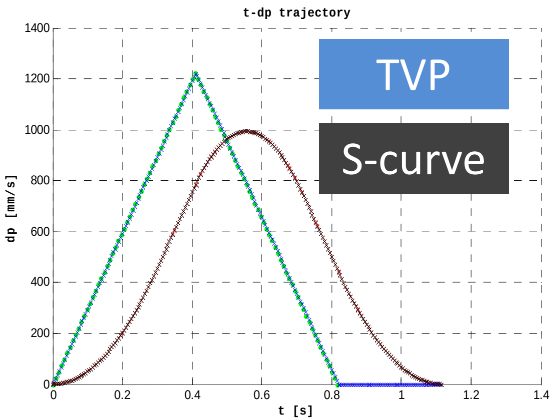
Pros: problem simplified by the path parameter
very close to true time-optimal trajectories

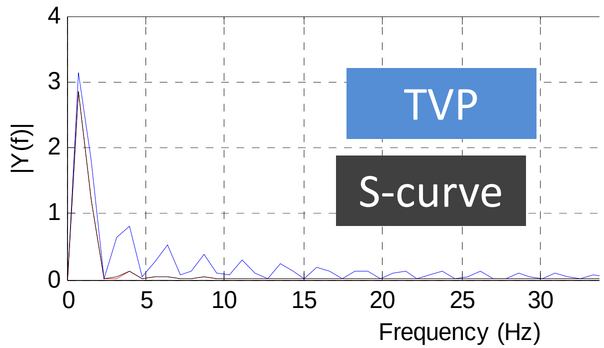
Cons: high CPU burden, infinite jerk (in general),
dynamic model never perfect

Shin and McKay (1985)
Bobrow *et al.* (1985)
Constantinescu and Croft (2000)

Well-Known Methods Smooth-Trajectories

- Argument
  ; time-optimal: too complicated, high frequencies (advanced control methods required)
  ; smooth trajectories can obtain faster settling times due to small residual vibrations.





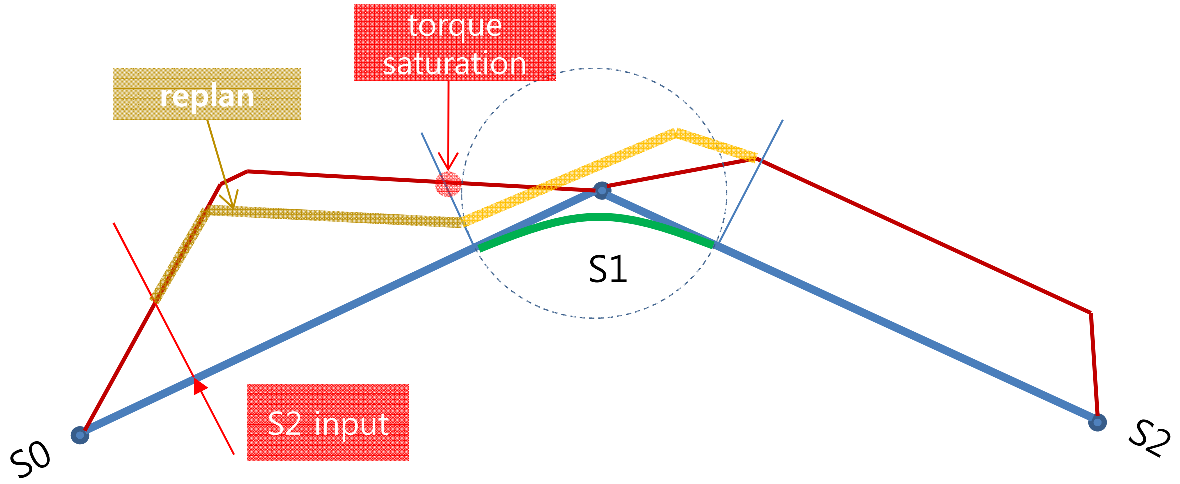
Pros: small oscillation, no special controllers needed

Cons: slow (no dynamics)
too many cases for non-zero boundary conditions
cannot completely suppress high freq.
natural freq. must be known

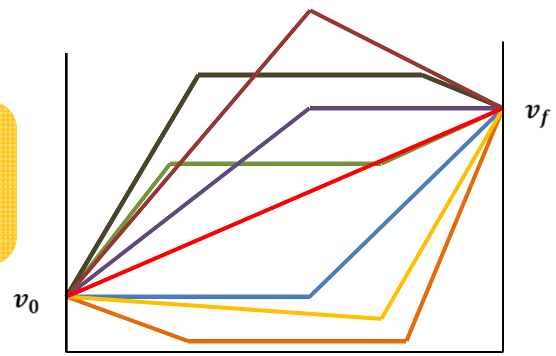
Meckl and Woods (1985)
Singer (1990)
Macfalane and Croft (2003)
Kroger and Walh (2010)

Challenges online planning

Online trajectory planning: A robot's trajectory must be planned (replanned) during motion for any (stationary) target given kinematic and dynamic constraints.



Trapezoid Velocity



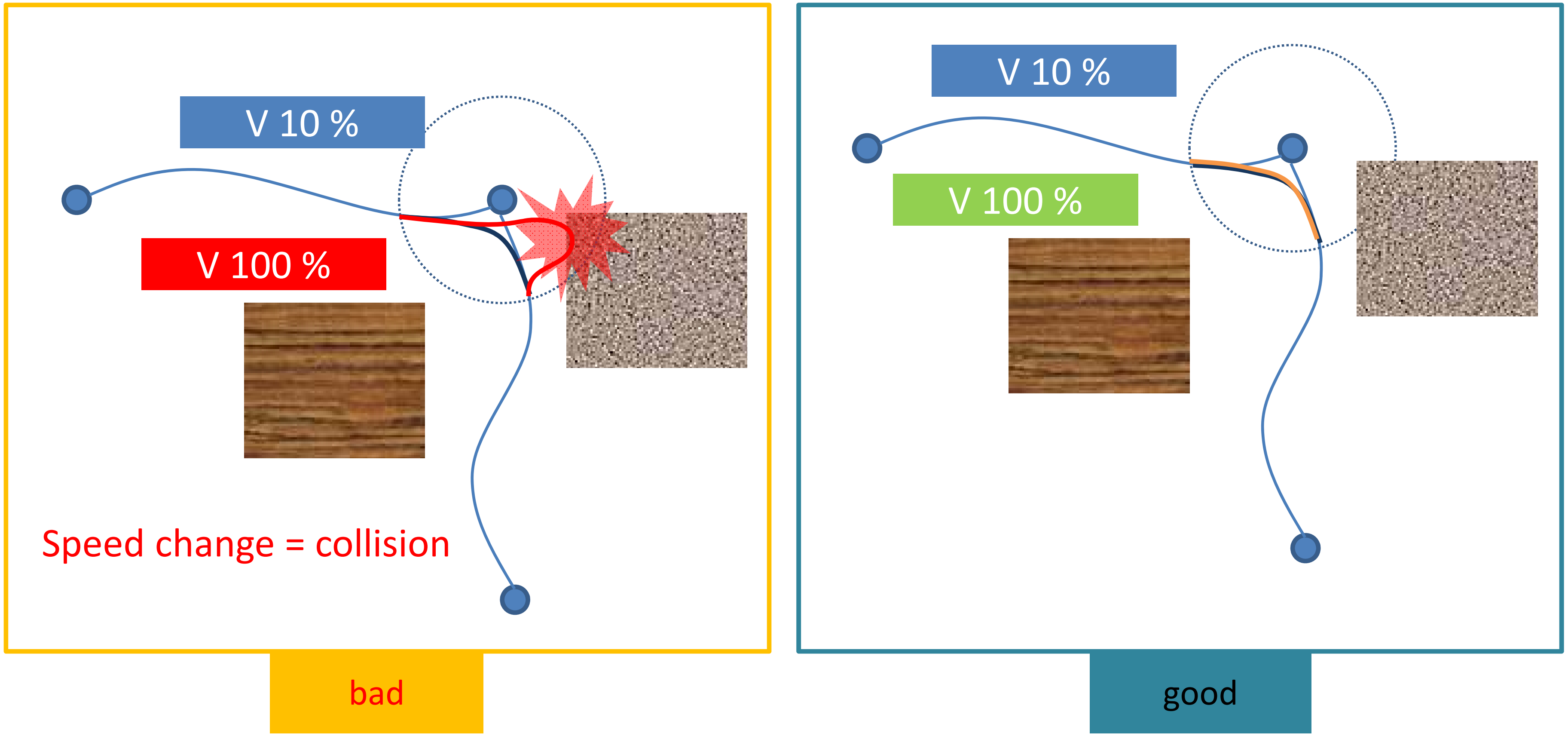
Non-zero boundary conditions

S-curves or higher polynomials?

- too many cases to consider
- prone to generate s/w errors

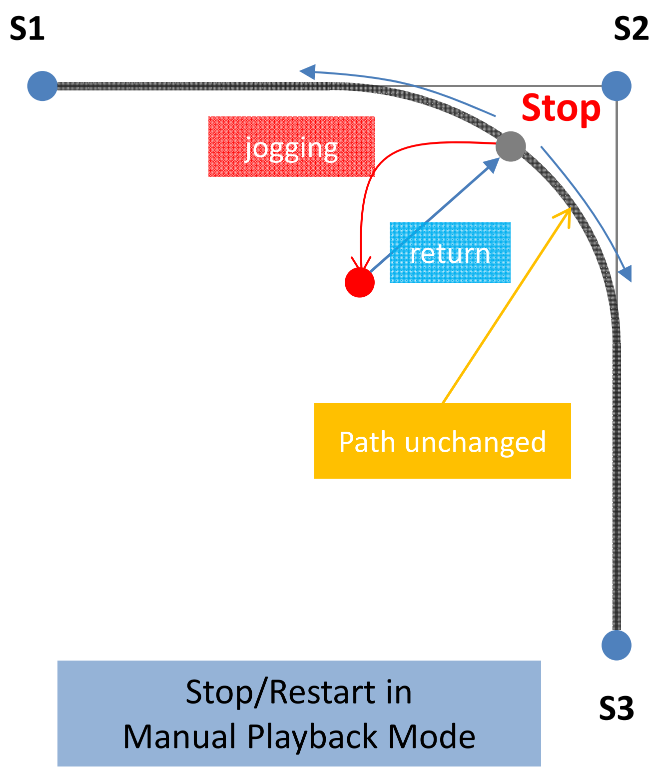
-> difficult to implement and maintain

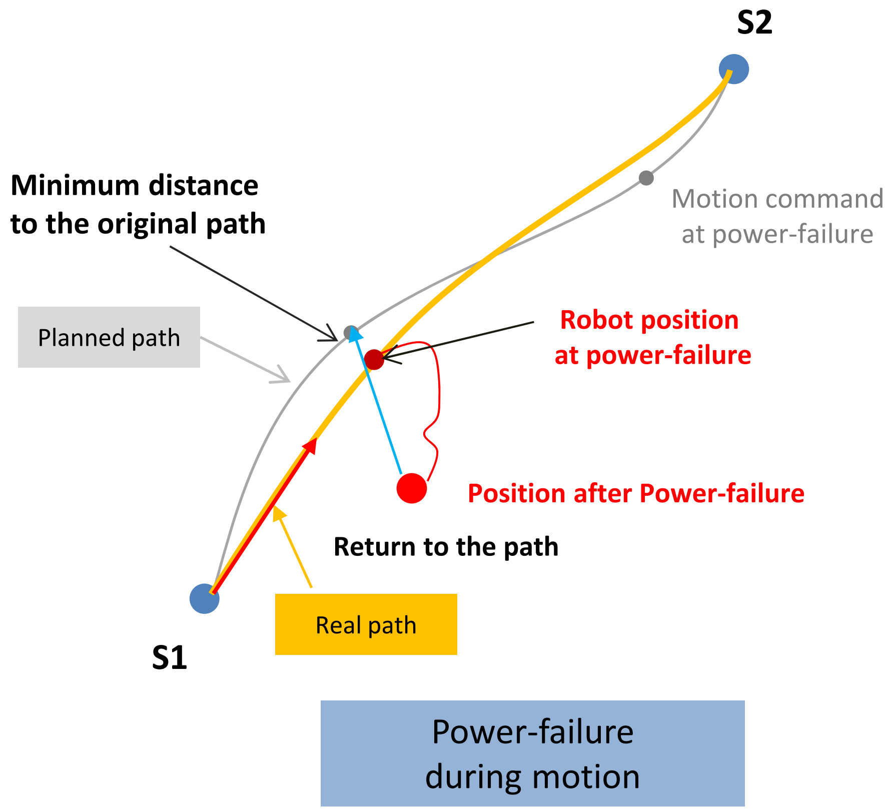
Challenges path and speed



Path must be the same regardless of speed changes.

Challenges path invariance for all operation conditions

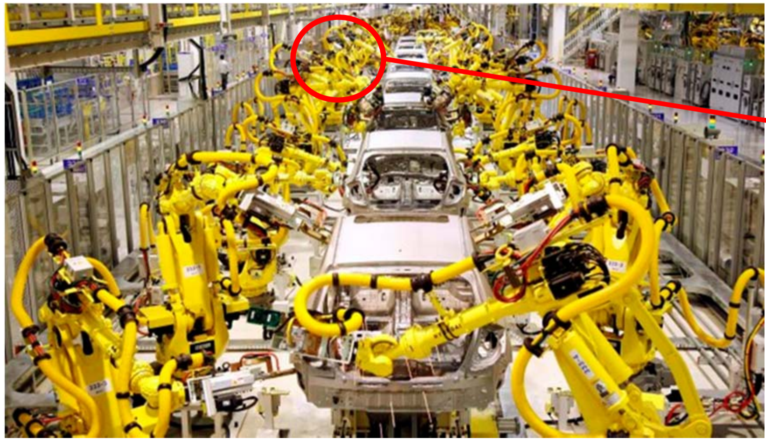




A programmed path must not be changed under any circumstances unless such a request is made by the user.

Path Recovery

Imagine you are in charge of this factory!
And there is a chance of black-out!



No power failure

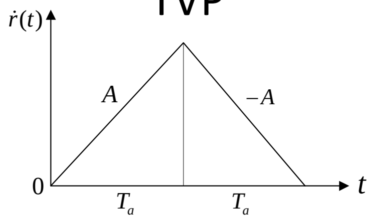
Power failure

Path Recovery

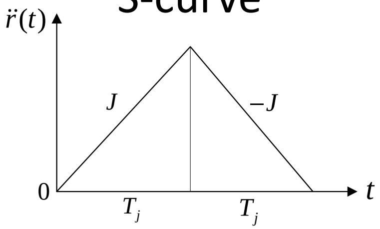
Trajectories Vs. Residual Vibrations

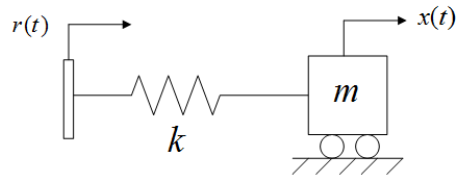
Frequency Analysis via Fourier Transform

TVP



S-curve





$$m\ddot{x} + k(x - r) = 0$$

$$R_{TVP}(j\omega) = \frac{A}{-\omega^2}\left(1 - e^{-jT_a\omega}\right)$$

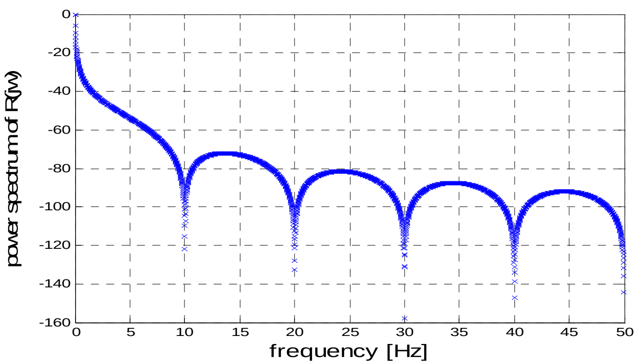
$$R_{S-curve}(j\omega) = \frac{J}{-j\omega^3}\left(1 - e^{-jT_j\omega}\right)$$

$$\frac{X(j\omega)}{R(j\omega)} = H(j\omega) = \frac{\omega_n^{\ 2}}{\omega_n^{\ 2} - \omega^2}$$

$$X_{TVP}(j\omega) = H(j\omega)\,R_{TVP}(j\omega) = \frac{A}{-\omega^2}\left(\frac{\omega_n^{\ 2}}{\omega_n^{\ 2} - \omega^2}\right)\left(1 - e^{-jT_a\omega}\right)$$

$$X_{S-curve}(j\omega) = H(j\omega)\,R_{S-curve}(j\omega) = \frac{J}{-j\omega^3}\left(\frac{\omega_n^{\ 2}}{\omega_n^{\ 2} - \omega^2}\right)\left(1 - e^{-jT_j\omega}\right)$$

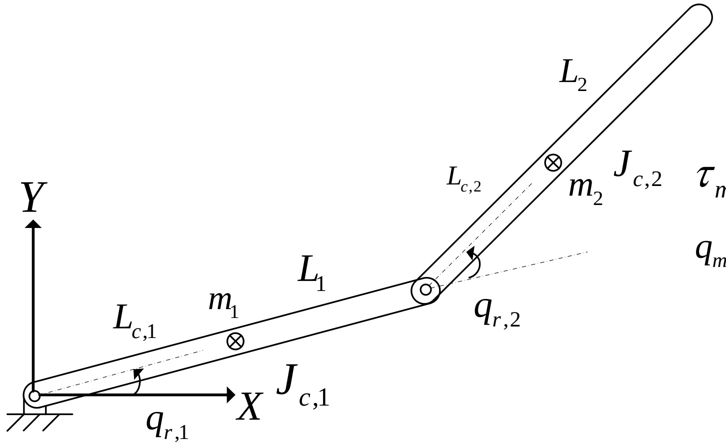
FRF of TVP



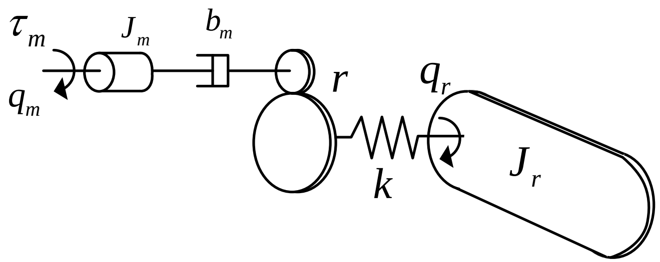
- Big A, Big J -> large Oscillation
- TVP Larger vibration than S-curve
- Vibration can be 0 at some T_a, T_j
- S-curves still have high freq.

Simulation dynamic model

Robot: 2DOF industrial Robot with flexible joints
Initial position: q_{r0} = [90, -90] [deg]
Natural frequencies: 7 Hz, 21 Hz at q_{r0}



Joint model

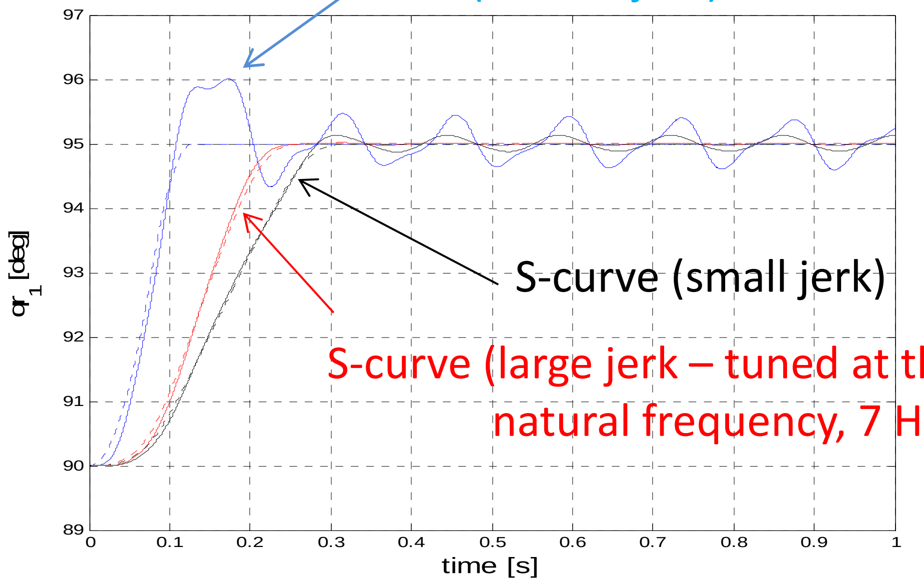


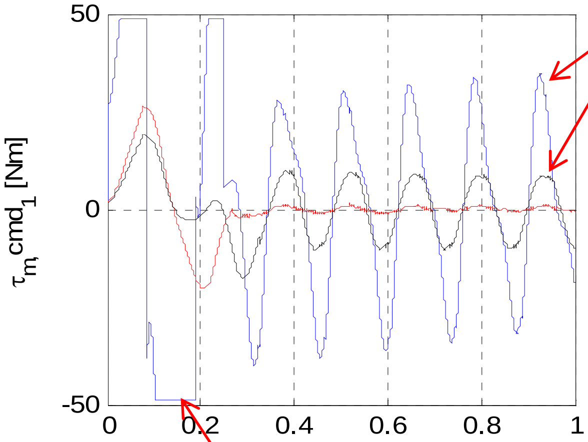
Parameter	Joint 1	Joint 2	Parameter	Joint 1	Joint 2
Mass [kg]	80	170	k [Nm/rad]	1010700	505350
Jr [kg.m2]	9.97	13.7	bm [Nm s/rad]	0.0281	0.0088
L [m]	0.87	1.05	Max. motor torque [Nm]	49	35.86
Lc [m]	0.38	0.2	r (gear ratio)	201	145

Simulation trajectories Vs. vibrations

Controller: Decentralized
PD controllers

First joint position

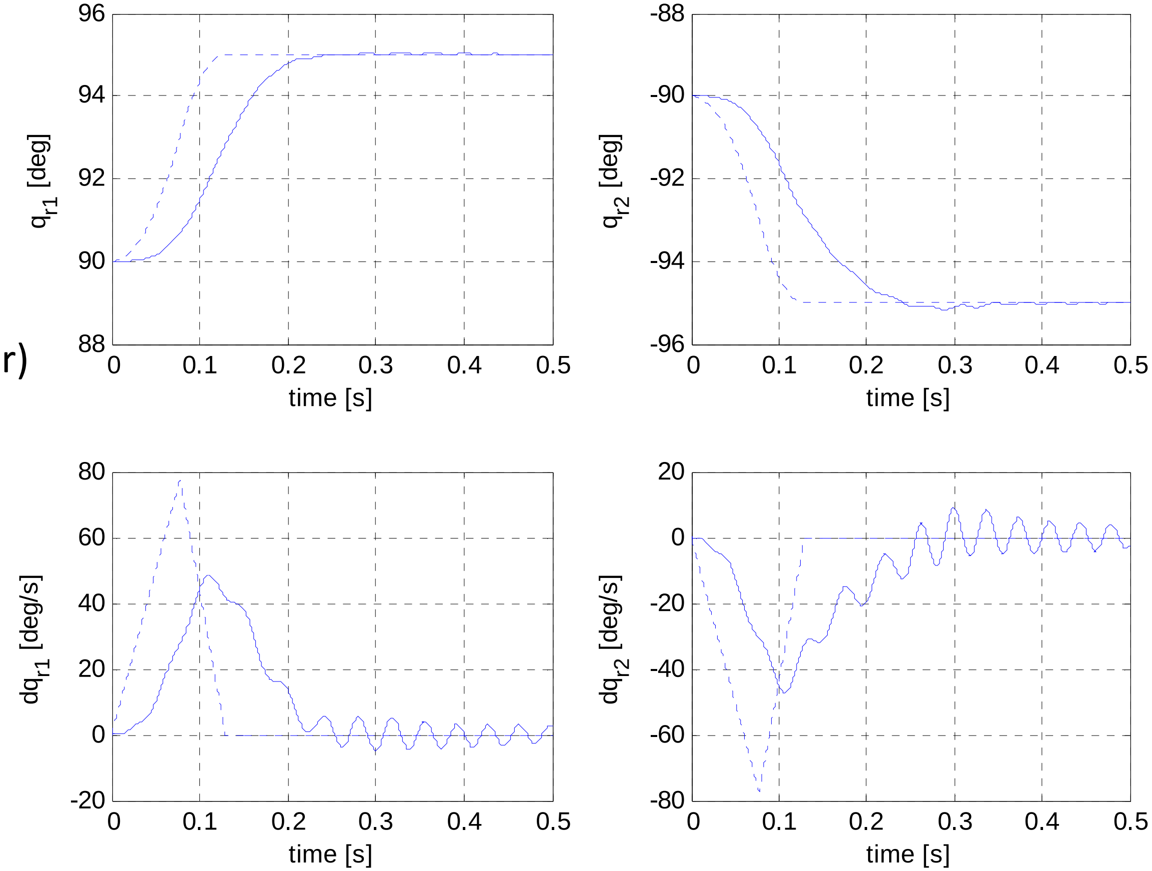




- Control performance is affected by trajectories.
- Trajectories must be band-limited.
- Such limitation of the band cannot be determined arbitrarily.

Simulation trajectories Vs. controller

Trajectory: TVP
Controller: decentralized
& linear
full-state feedback
(linear state-observer)
fixed gain by pole-placement



- Large tracking errors
- Large oscillations

-> Decentralized and linear control methods do not work well.
-> A more advanced control method is needed.

Conclusions

- Trajectory planning for industrial robots is challenging.
  ; online planning, safety, efficiency, complex kinematics and dynamics

- Traditionally, a good trajectory is regarded as either time-optimal or smooth.

- Time-optimal trajectories
  ; high CPU burden and high frequency components

- Smooth trajectories
  ; too slow, still complex (high order polynomials), vague jerk limitation

- What is the best trajectory for industrial robots?
  ; not clear but TVP is still widely used!
  ; it depends on servo controller.