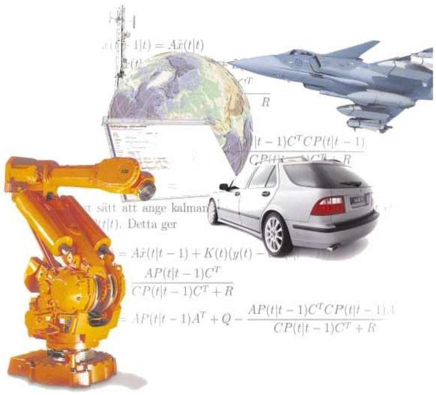
Towards improved performance for industrial robots



Mikael Norrlöf
ISIS/Division of Automatic Control, Linköping University
mino@isy.liu.se

Special thanks to:
Mattias Björkman, Torgny Brogårdh, Svante Gunnarsson, Rickard Karlsson, Stig Moberg and Erik Wernholt

The robotics acivities within ISIS

- Iterative Learning Control
- Robot trajectory generation and optimization
- Robot modeling and identification
- Robot control
  - Joint level control
  - Multivariable control
  - Sensor fusion
- Robot diagnosis

Common factor for all the activities:

Increased robot performance!

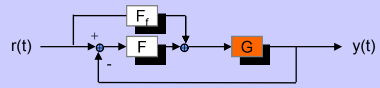
The robot system and its components

- Links
- Joints
- Motors
- Gears
- Bearings

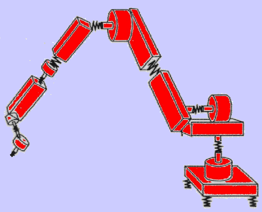
Main problems:

- Flexibilities
- Friction
- Sensor and actuator uncertainties

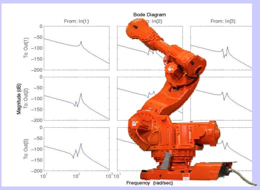
ISIS activities



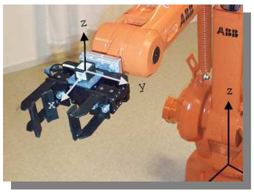
Control design



Modeling



Identification



Sensor fusion

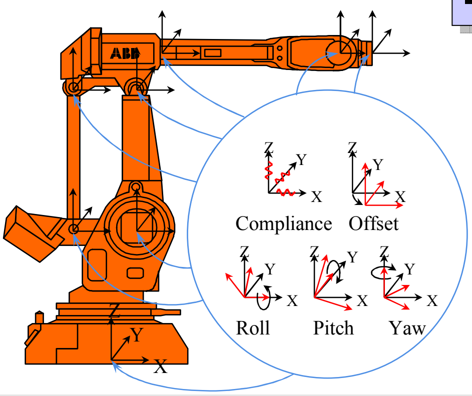
$$\max_{a} a_I$$
$$\text{s.t.} \quad a_{min} \leq a \leq a_{max}$$
$$0 \leq v(a) \leq v_d$$
$$\dot{\phi}_{min} \leq \dot{\phi}(a) \leq \dot{\phi}_{max}$$
$$\ddot{\phi}_{min} \leq \ddot{\phi}(a) \leq \ddot{\phi}_{max}$$

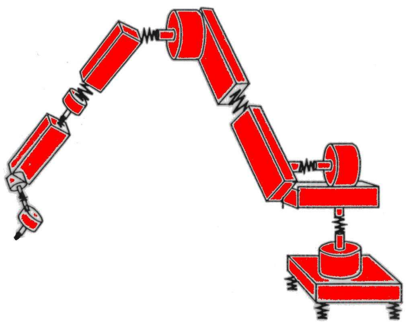
Trajectory generation and optimization

Mikael Norrlöf
2004 ISIS Workshop

Robot modeling

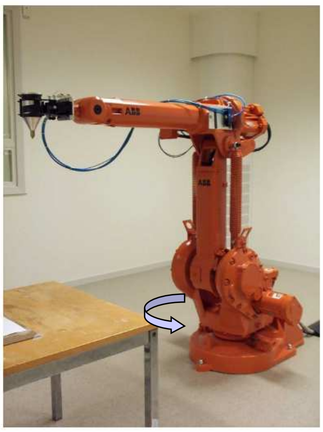
- Kinematics
- Elastostatic
- Rigid body dynamics
- Elastodynamic

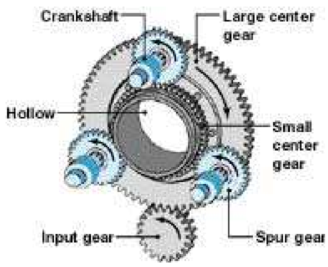


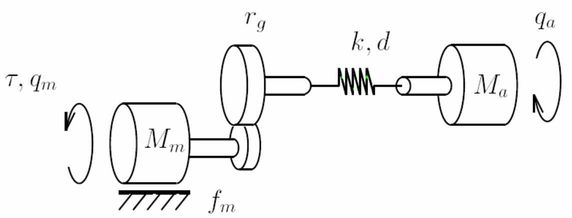


Joint level modeling

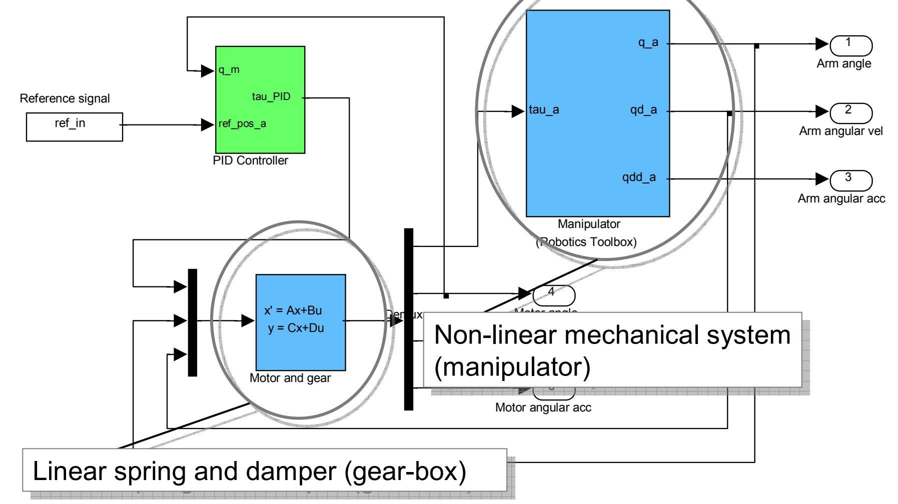
Linear system approximation.



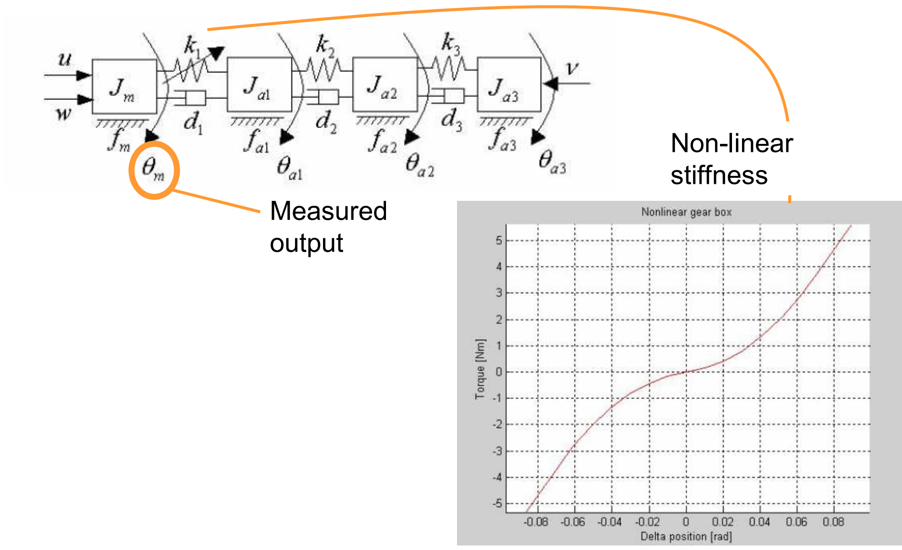




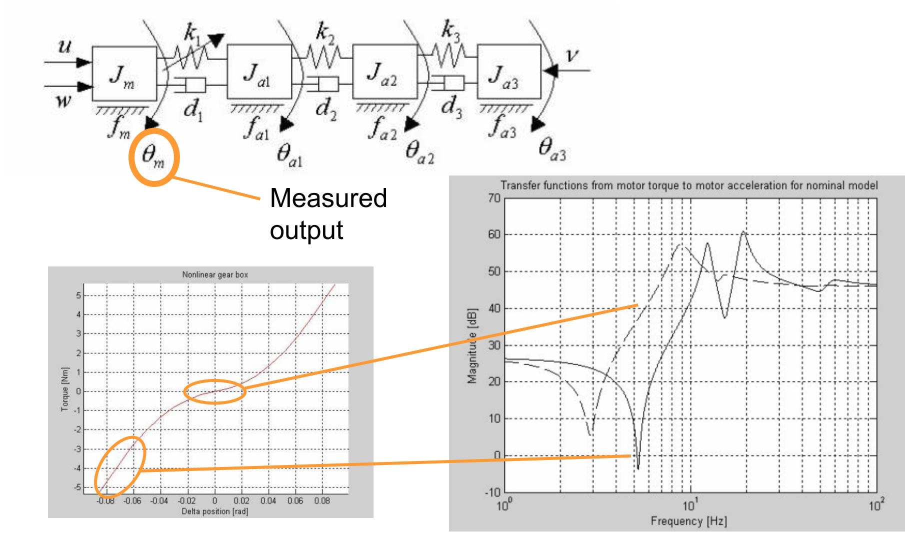
Robot modeling



Non-linear joint model

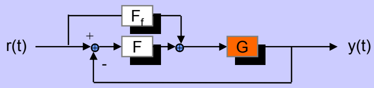


Non-linear joint model



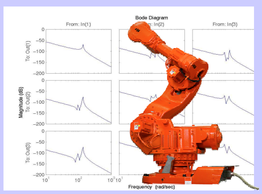
Mikael Norrlöf
2004 ISIS Workshop

ISIS activities



Control design

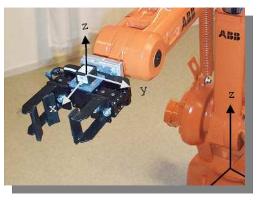
Modeling



Identification

$$\max_a a_l$$
s.t. $a_{min} \le a \le a_{max}$
$0 \le v(a) \le v_d$
$\dot{\phi}_{min} \le \dot{\phi}(a) \le \dot{\phi}_{max}$
$\ddot{\phi}_{min} \le \ddot{\phi}(a) \le \ddot{\phi}_{max}$

Trajectory generation and optimization

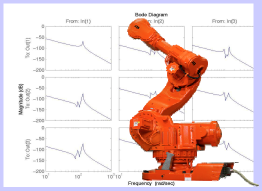


Sensor fusion

Mikael Norrlöf
2004 ISIS Workshop

Identification

- Choice of excitation signal
- Measurements
- Stochastic disturbances
- Deterministic disturbances
- Transient and stationary behavior
- Non-linear system

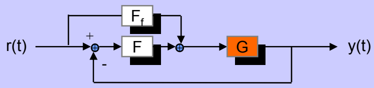


Identification

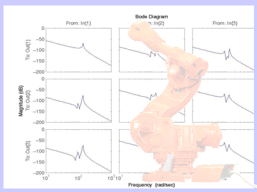
Mikael Norrlöf
2004 ISIS Workshop

ISIS activities

Modeling



Control design



Identification

$$\max_{a} a_1$$

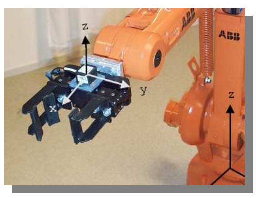
$$\text{s.t.} \quad a_{min} \le a \le a_{max}$$

$$0 \le v(a) \le v_d$$

$$\dot{\phi}_{min} \le \dot{\phi}(a) \le \dot{\phi}_{max}$$

$$\ddot{\phi}_{min} \le \ddot{\phi}(a) \le \ddot{\phi}_{max}$$

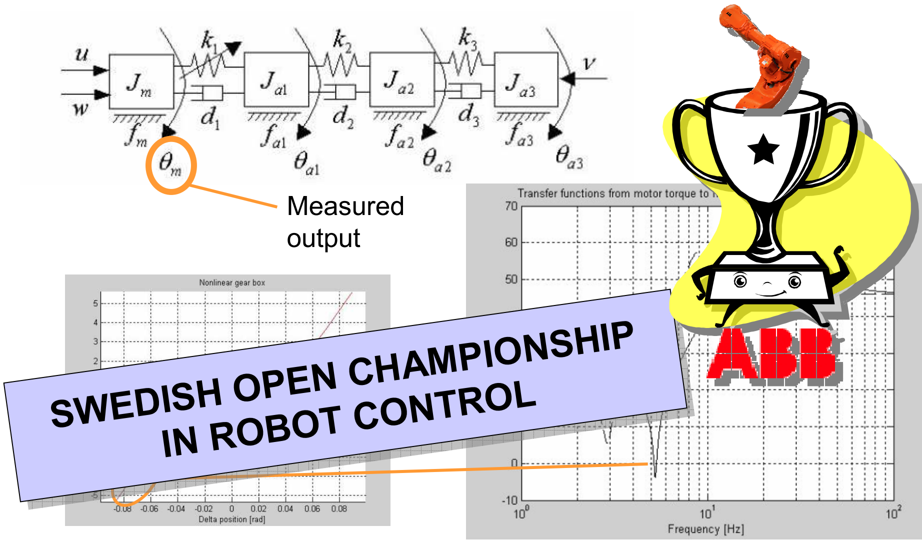
Trajectory generation and optimization



Sensor fusion

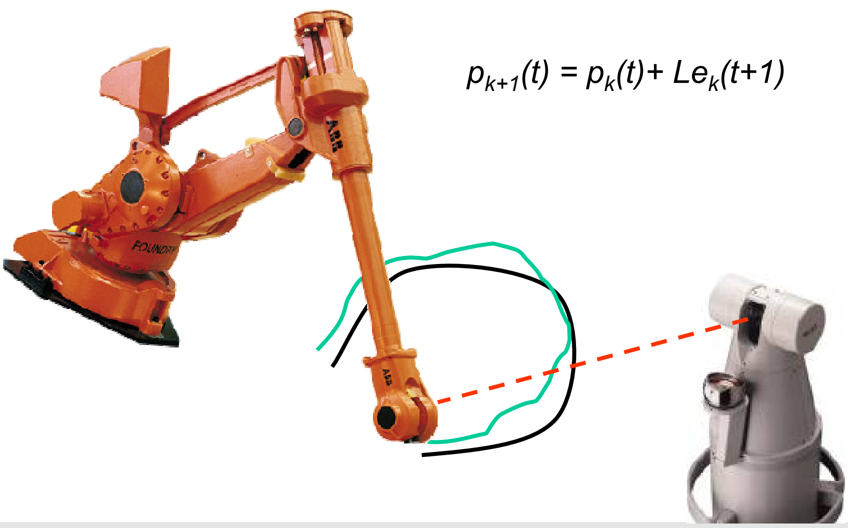
Mikael Norrlöf
2004 ISIS Workshop

Non-linear joint model



Mikael Norrlöf
2004 ISIS Workshop

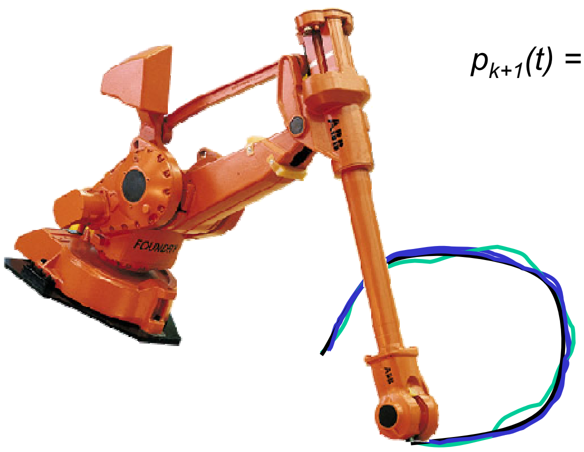
The iterative learning control technique



$p_{k+1}(t) = p_k(t) + Le_k(t+1)$

Mikael Norrlöf
2004 ISIS Workshop

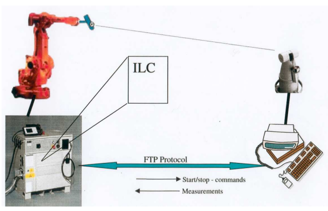
The iterative learning control technique

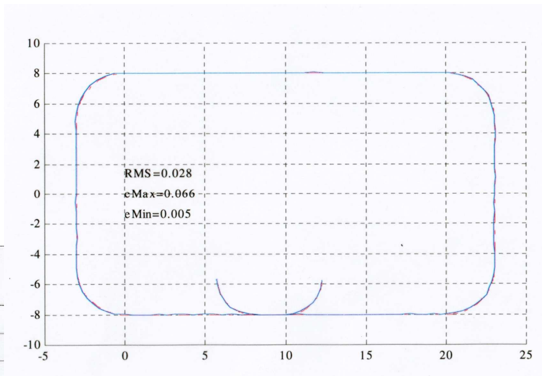


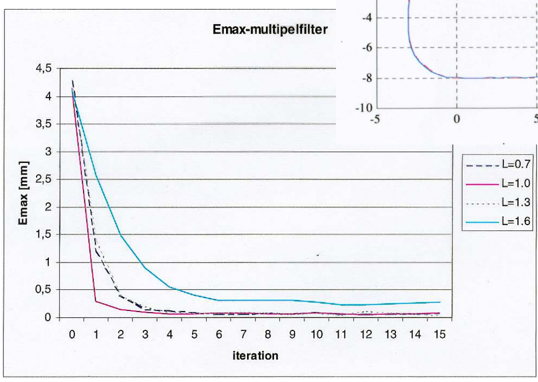
$$p_{k+1}(t) = p_k(t) + Le_k(t+1)$$

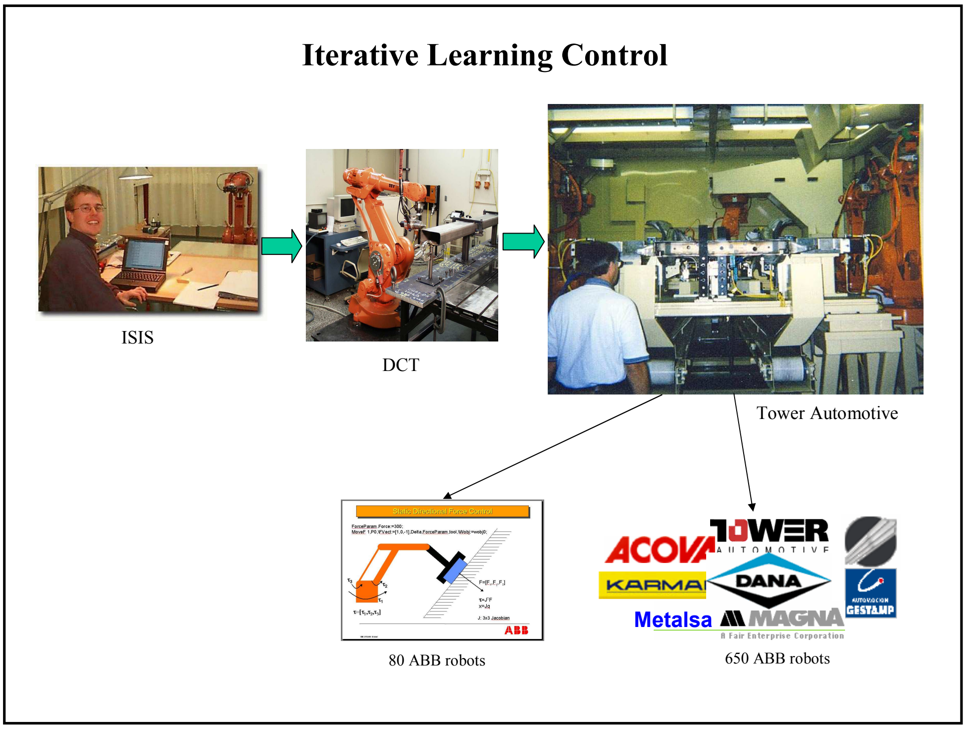
Mikael Norrlöf
2004 ISIS Workshop

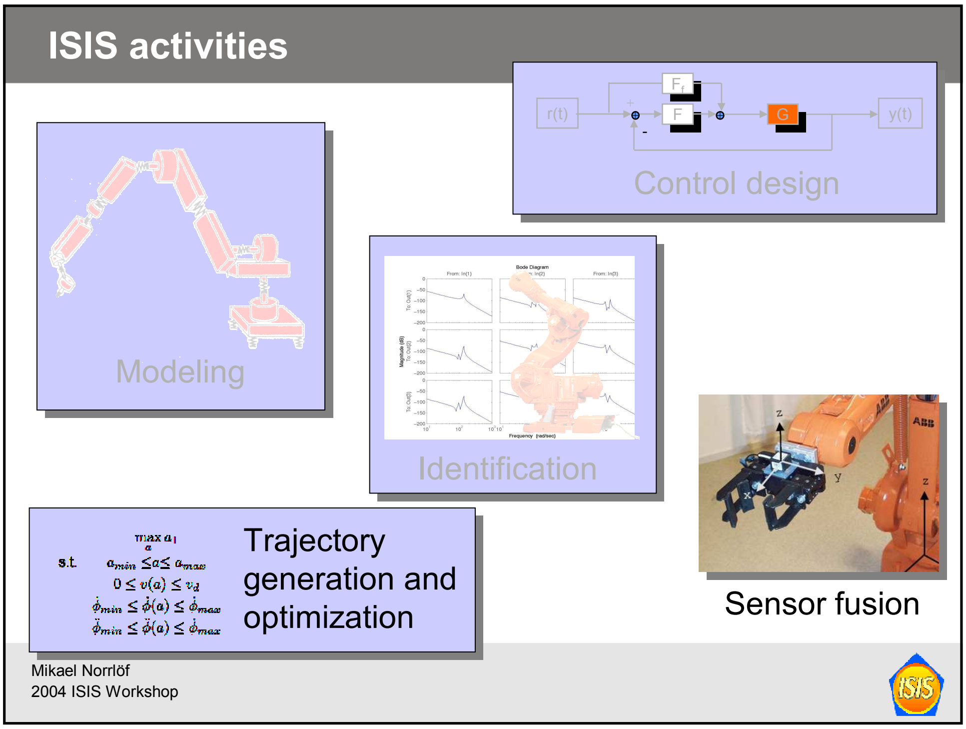
Iterative Learning Control








Iterative Learning Control
ISIS
DCT
Tower Automotive
80 ABB robots
650 ABB robots
ACOVA
TOWER AUTOMOTIVE
KARMAI
DANA
Metalsa
MAGNA
GESTAMP


ISIS activities
Modeling
r(t)
y(t)
G
Control design
Identification
Trajectory generation and optimization
Sensor fusion
Mikael Norrlöf
2004 ISIS Workshop

Sensor fusion

The basic idea:

”Use measurements from a sensor mounted at the tool to get better estimates of the position, velocity, and acceleration.”

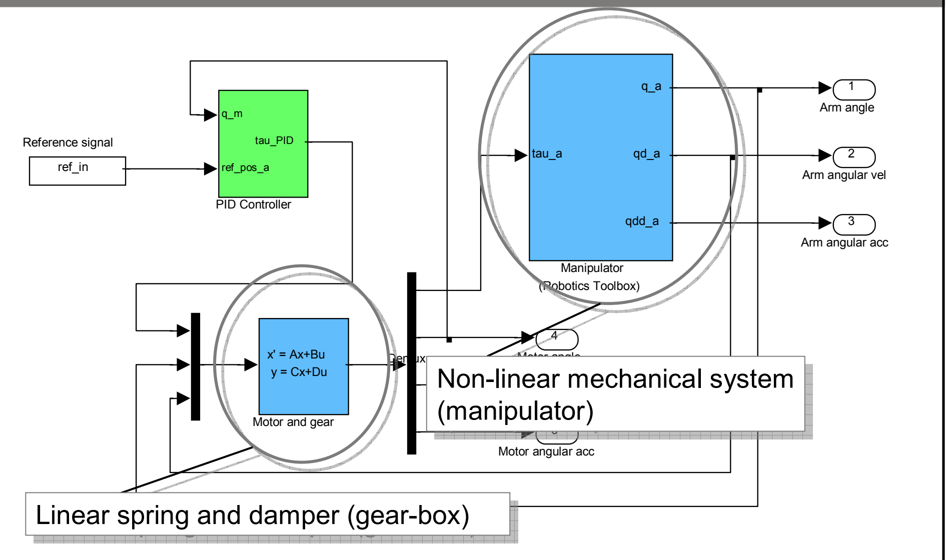
Sensor fusion based on Bayesian techniques

Using additional sensors

What can be achieved?

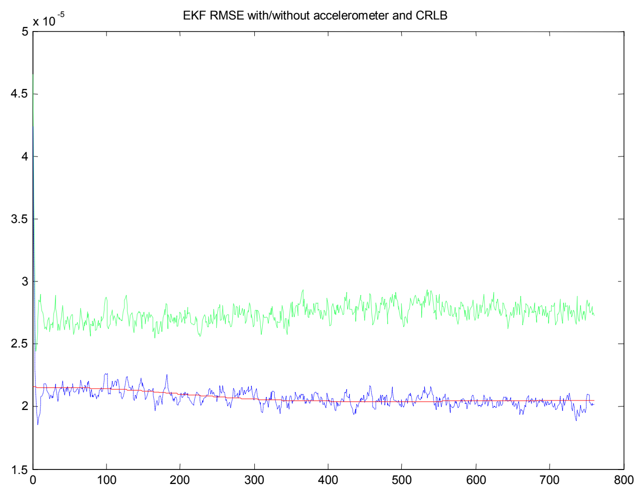
- Increased robustness
- Higher accuracy
- Increased stiffness

The "true" system



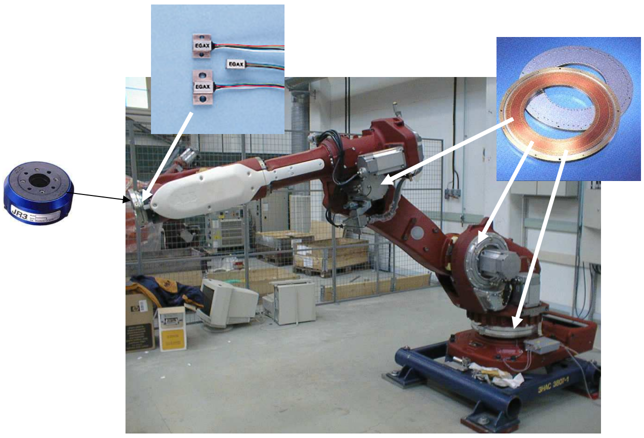
Mikael Norrlöf
2004 ISIS Workshop

Evaluation of arm position estimation

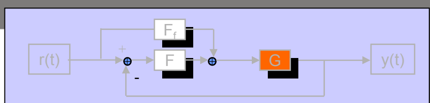


Mikael Norrlöf
2004 ISIS Workshop

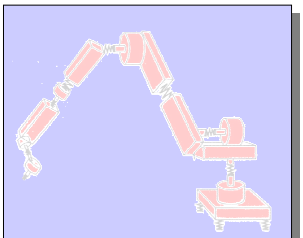
Other possible sensors



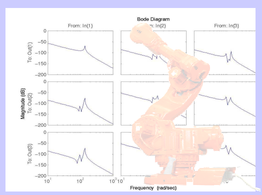
ISIS activities



Control design



Modeling



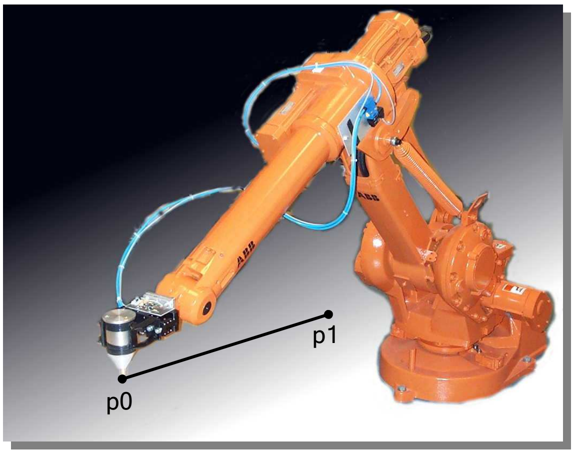
Identification

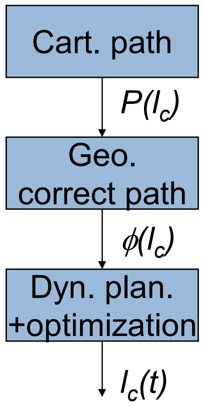
$$\max_{a} a_1$$
$$\text{s.t.} \quad a_{min} \leq a \leq a_{max}$$
$$0 \leq v(a) \leq v_d$$
$$\dot{\phi}_{min} \leq \dot{\phi}(a) \leq \dot{\phi}_{max}$$
$$\ddot{\phi}_{min} \leq \ddot{\phi}(a) \leq \ddot{\phi}_{max}$$

Trajectory generation and optimization

Sensor fusion

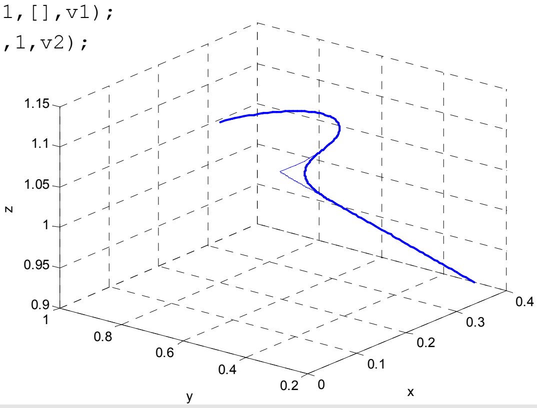
The trajectory generation problem





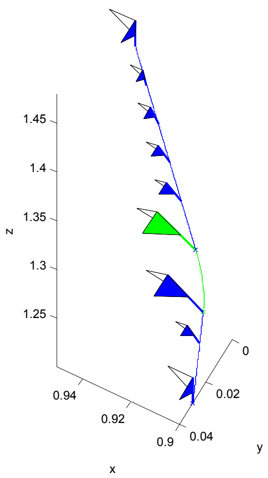
Path generation Toolbox in Matlab

```
p1 = [0.4,0.3,0.9]; p2 = [0.1,0.45,1.1];
p3 = [0.3,0.60,1.1]; p4 = [0.2,0.8,1.1];
zone1 = 0.1; zonemethod = 1; v1 = 0.25; v2 = 0.25;
esec = emptysec(p1);
lsec = moveline(esec,p2,zone1,[],v1);
csec = movecirc(lsec,p3,p4,0,1,v2);
rpath = makepath(lsec,csec)
```



Path generation Toolbox in Matlab

Orientation information will be added in PGT v0.3



Dynamic optimization

- Path: $P(l_c)$, $\phi(l_c)$
- Path speed and acceleration:

$$v = \left\| \frac{dP}{dl_c} \right\| \frac{dl_c}{dt}, \quad a_{path} = \left\| \frac{dP}{dl_c} \right\| \frac{d^2 l_c}{dt^2}$$

$$\dot{\phi} = \frac{d\phi}{dl_c}\frac{dl_c}{dt}, \quad \ddot{\phi} = \frac{d^2\phi}{dl_c^2}\left(\frac{dl_c}{dt}\right)^2 + \frac{d\phi}{dl_c}\frac{d^2 l_c}{dt^2}$$

Dynamic optimization

Let $l(t) = \frac{a(t-t_p)^2}{2} + v(t-t_p) + l_p, \quad t \in [t_p, t_n]$

A (sub) optimal minimum time trajectory is found by solving the following LP problem

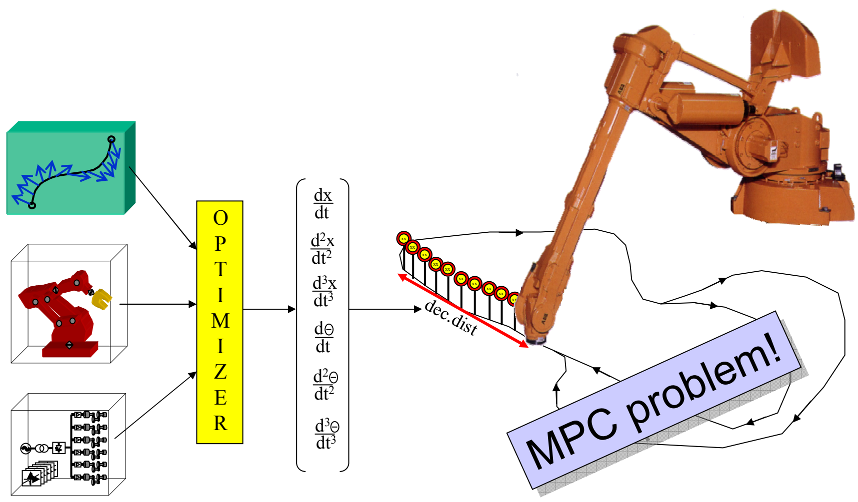
$$\max_a a_1$$

s.t.

$$a_{min} \leq a \leq a_{max}$$
$$0 \leq v(a) \leq v_d$$
$$\dot{\phi}_{min} \leq \dot{\phi}(a) \leq \dot{\phi}_{max}$$
$$\ddot{\phi}_{min} \leq \ddot{\phi}(a) \leq \dot{\phi}_{max}$$

Mikael Norrlöf
2004 ISIS Workshop

Dynamic optimization

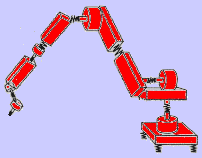


Mikael Norrlöf
2004 ISIS Workshop

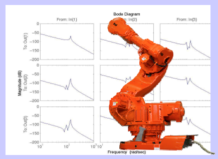
Conclusions

Impact on current and future products

- Auto tune
- Control design



Modeling

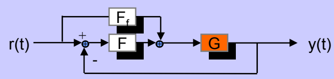


Identification

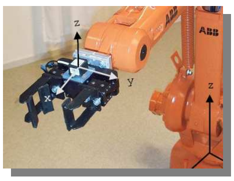
Conclusions

Impact on current and future products

- Iterative Learning Control
- More flexible mechanical design



Control design



Sensor fusion

Conclusions

Impact on current and future products

- Make better use of the robot performance
- Reduced price

$$\begin{aligned} &\max_a a_1 \\ \text{s.t.} \quad & a_{min} \le a \le a_{max} \\ & 0 \le v(a) \le v_d \\ & \dot{\phi}_{min} \le \dot{\phi}(a) \le \dot{\phi}_{max} \\ & \ddot{\phi}_{min} \le \ddot{\phi}(a) \le \dot{\phi}_{max} \end{aligned}$$

Trajectory generation and optimization

Conclusions

"ISIS has activities in areas central for the future developments in industrial robotics"