Nonlinear Observers:
Collision and Error Detection

Motivation

- Safe Human-Robot Interaction
- Improvement of controller performance (for impedance control or trajectory tracking) through friction compensation

Safety in Human-Robot interaction can be achieved through:

- light-weight, compliant robot design
- Sensors (cameras, proximity sensors…
- human-centered motion planning
- safe and robust control strategies
- prevention, prediction, **recognition and handling of collisions**

Collision, Handled as a System Error

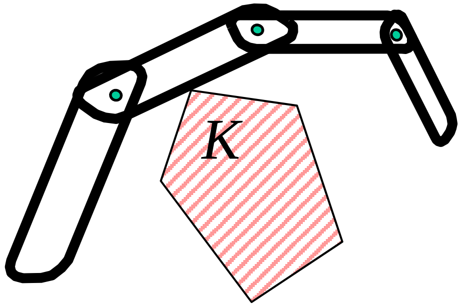
• robot model:

• Collision force
• friction forcet
• joint error
• …

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q) = \tau + \tau_K$$

For external collision: $\tau_K = J_K^T(q) F_K$

Transposed Jacobian
At contact point K



- using proprioceptive (internal) sensors (position, torque)
- Contact at arbitrary point on the robot
- Simplifying assumption
  - One contact point
  - Robot is an open kinematic chain

Possible Approaches for Observation of Contact Point

1. $\tau_d \leftrightarrow \tau$:Compare torques on the desired trajectory with commanded torques

$$\tau_d = M(q_d)\ddot{q}_d + C(q_d, \dot{q}_d)\dot{q}_d + g(q_d)$$

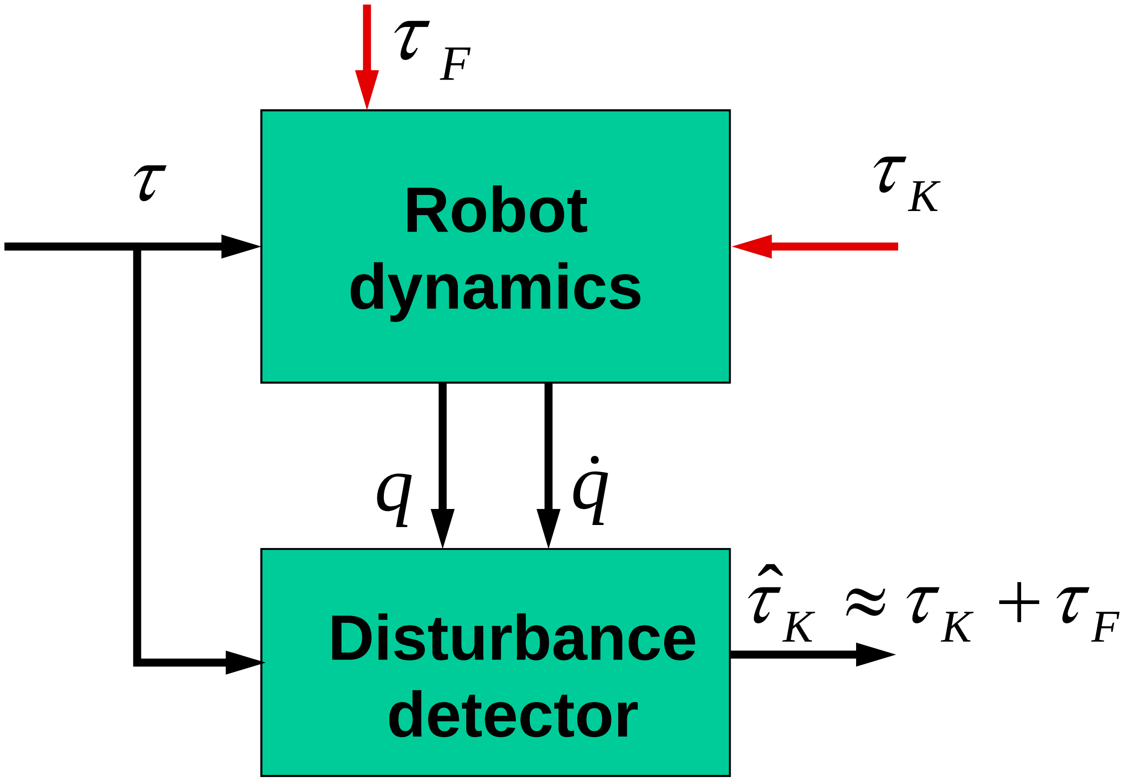
Disadvantage: controller dynamics not considered

2. $\tau_M \leftrightarrow \tau_J$: Compare torques on the real trajectory with commanded torques

$$\ddot{q}_N = \frac{d\dot{q}}{dt} \qquad \tau_M = M(q)\ddot{q}_N + C(q, \dot{q})\dot{q} + g(q)$$

Disadvantage: noisy acceleration signal

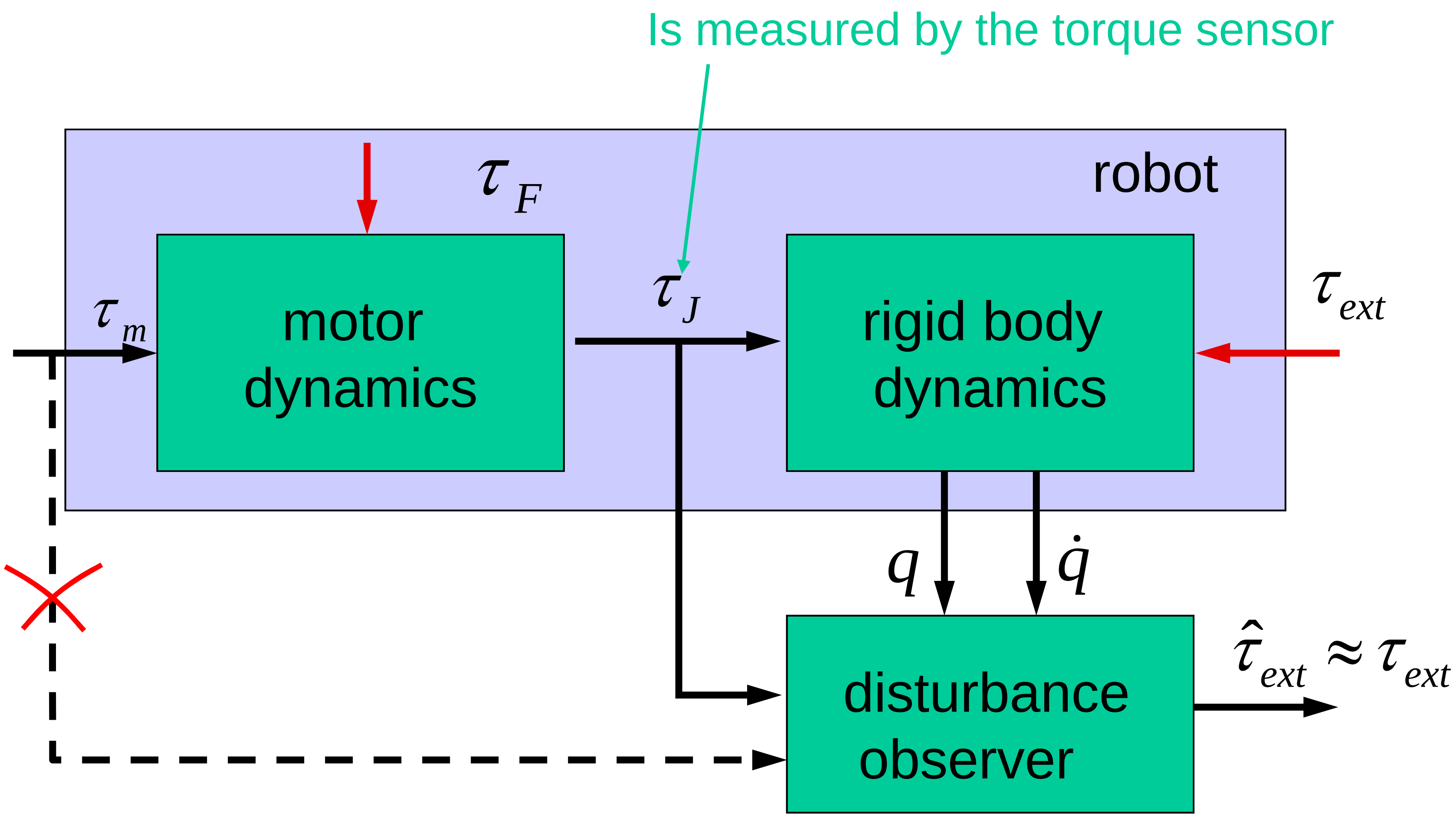
Observation of the Disturbance Torque



One can detect only the sum of disturbance torque and friction torque

The structure can be used for friction compensation if the robot is not in contact with the environment

Disturbance Observer for Collision Detection



IROS'06
with Alessandro De Luca

Momentum equation

momentum: $p = M(q)\dot{q}$

$$\dot{p} = M(q)\ddot{q} + \dot{M}(q)\dot{q}$$

$\Downarrow \dot{M} = C + C^T$ standard robot property, here without proof

$$\dot{p} = \underline{M(q)\ddot{q} + C(q,\dot{q})\dot{q}} + C^T(q,\dot{q})\dot{q}$$

By inserting in the dynamics equation

$$\underline{M(q)\ddot{q} + C(q,\dot{q})\dot{q}} + g(q) = \tau_{tot} \qquad \tau_{tot} = \tau + \tau_k$$

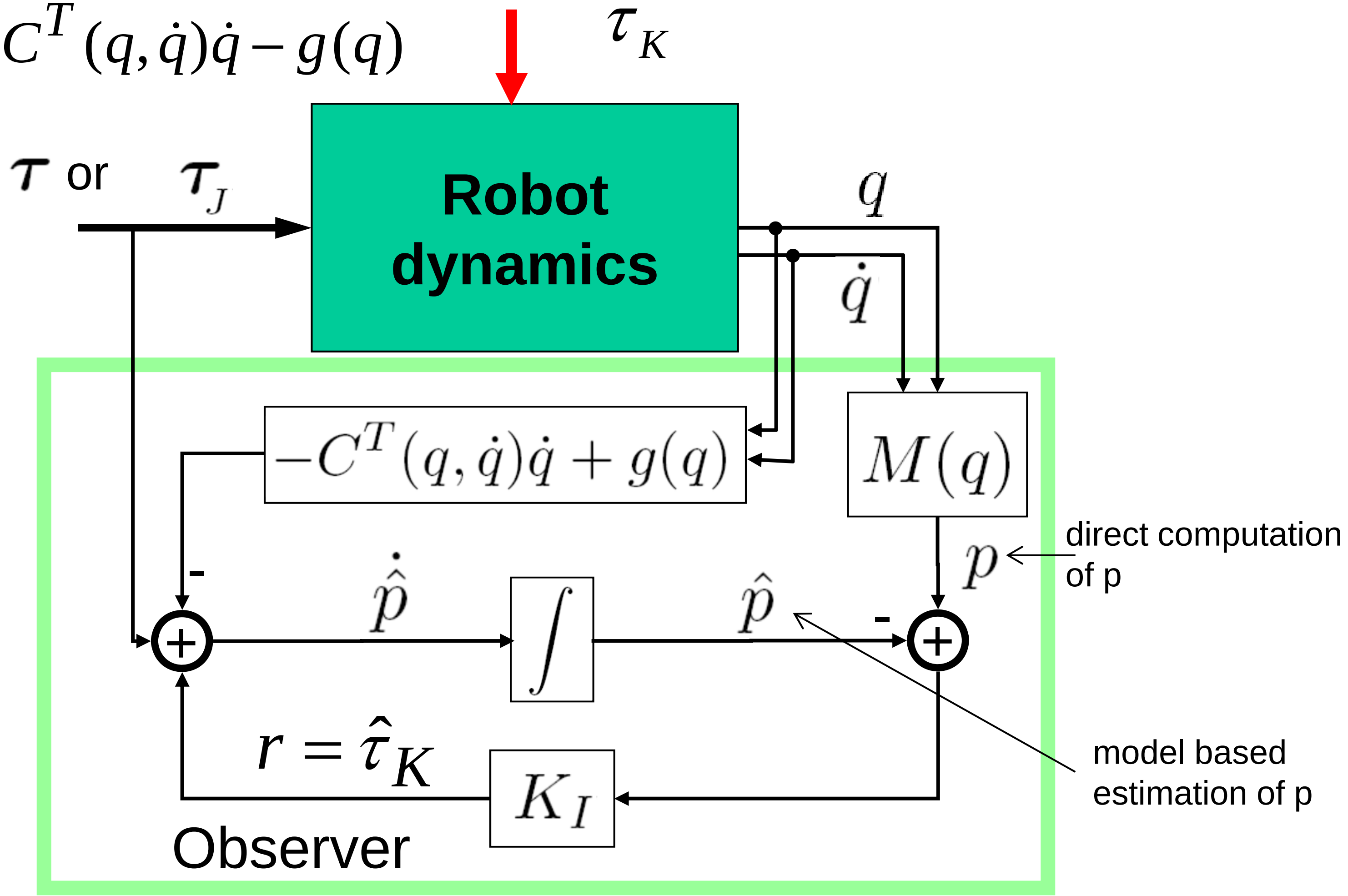
One obtains the momentum equation

$$\dot{p} = \tau_{\text{tot}} + C^T(q,\dot{q})\dot{q} - g(q)$$

Decoupled relation

Momentum Based Collision Detection

$$\dot{p} = \tau + \tau_k + C^T(q,\dot{q})\dot{q} - g(q)$$



$$\hat{\tau}_k(t) = K_I\left[\, p(t) - \int_0^t \left(\tau + \hat{\tau}_k + C(q,\dot{q})\dot{q} - g(q)\right)dt - p(0)\,\right]$$

$\hat{\tau}_K(0) = 0$

$K_I > 0$, diagonal

Observer Dynamics

By differentiating, one gets

$$\dot{\hat{\tau}}_k(t) = K_I\left[\dot{p}(t) - \left(\tau + \hat{\tau}_k + C(q,\dot{q})\dot{q} - g(q)\right)\right]$$

Because we have

$$\dot{p}(t) = \tau + \tau_k + C(q,\dot{q})\dot{q} - g(q)$$

=> linear, decoupled, first order dynamics

$$\dot{\hat{\tau}}_k(t) + K_I\hat{\tau}_k = K_I\tau_k$$

Or, using the Laplace-Transformation:

$$\hat{\tau}_{k\,i}(s) = \frac{\tau_{ki}(s)}{\frac{1}{K_{Ii}}s + 1}$$

Discussion

- Ideal case (no measurement noise)

$$K_I \to \infty \quad \Rightarrow \quad \boxed{\hat{\tau}_K \approx \tau_K}$$

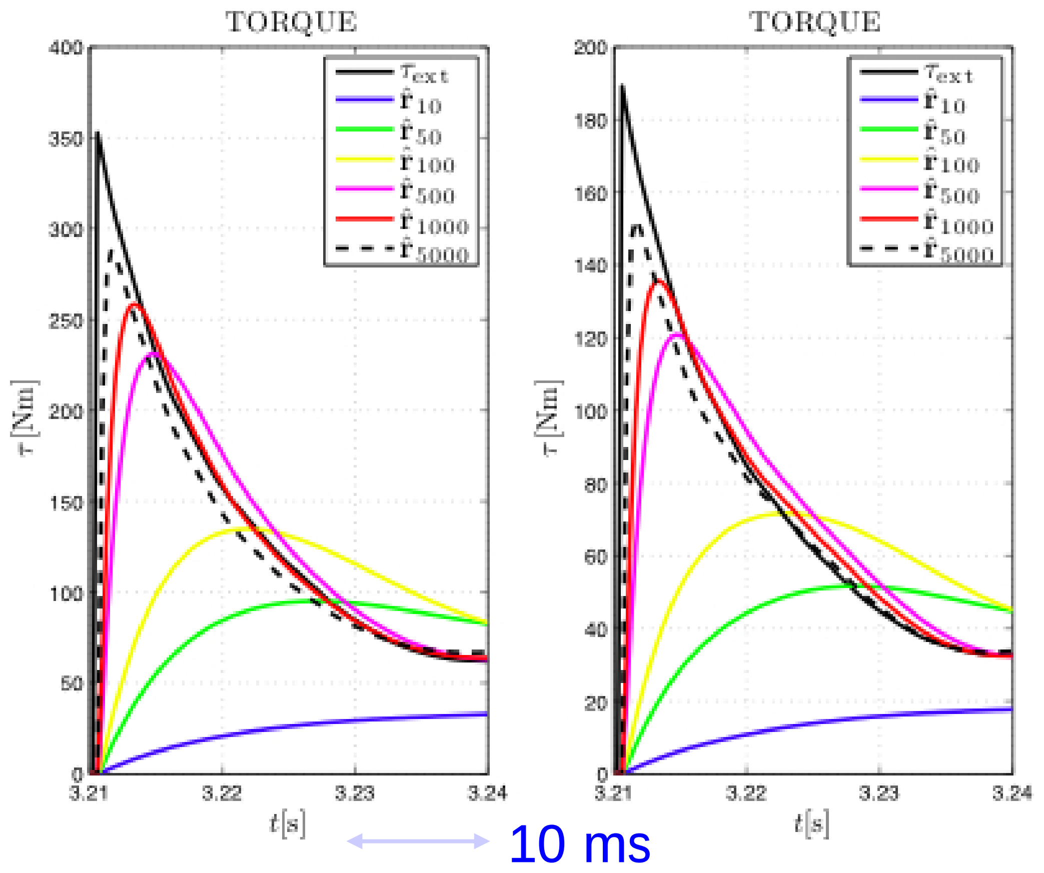
- Localization: collision is above joint i

$$\boldsymbol{r} = \begin{bmatrix} * & \dots & * & * & \underset{\underset{i+1}{\uparrow}}{0} & \dots & \underset{\underset{N}{\uparrow}}{0} \end{bmatrix}^T$$

Choice of the Gain K_I

Simulation results for KUKA light-weight robot III (collision at TCP)

Axis 2
@30°/s



Axis 4
@200°/s

Reaction Strategies

Possible reaction strategies after collision detection in position control mode:

- Strategy 1: stop the robot
- Strategy 2: switch to gravity compensation
  (robot is free floating)

$$\tau = g(q)$$

- Strategy 3: „reflex reaction“, fast movement is force direction

$$\tau = g(q) + K_R \hat{\tau}_K$$

- Strategy 4: Slowing down, ot reversing teh trajectory by modifying the interpolator in position control mode

$$\dot{\theta}_d = K_R \hat{\tau}_K$$

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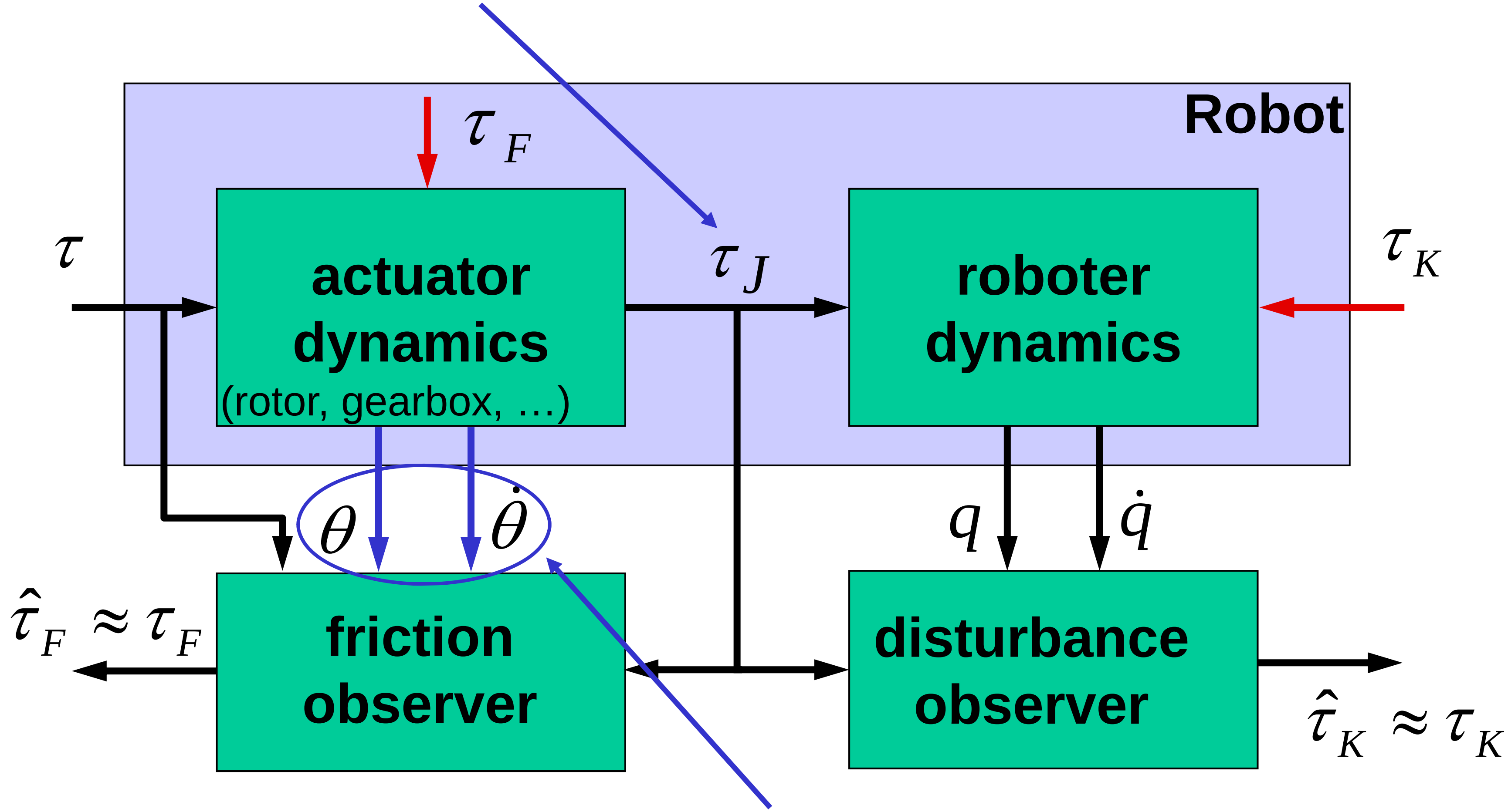
Separate Observation of Force and Friction

Using the torque sensor, the same approach can be applied for friction identification on the actuator side



Only for elastic joints, otherwise $\theta = q$