Model-based (sensorless) collision detection and localization

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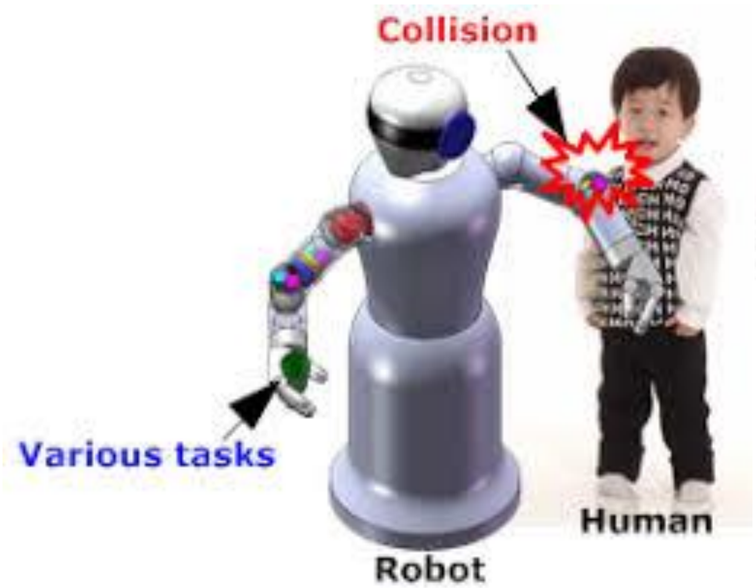
Introduction

- Collision monitoring for safe pHRI with residual method based on generalized momentum
- Simulations on YuMi (ABB, 2015): lightweight collaborative robot with two 7R arms



The residual method for collision detection and localization

Residual dynamics - 1

$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{c}(\mathbf{q}, \dot{\mathbf{q}}) + \mathbf{g}(\mathbf{q}) + \boldsymbol{\tau}_{\mathbf{f}} = \boldsymbol{\tau}_{\mathbf{m}} + \boldsymbol{\tau}_{\mathbf{k}}$$

$$\dot{\mathbf{r}} = \mathbf{K}_{\mathbf{o}}(\boldsymbol{\tau}_{\mathbf{k}} - \mathbf{r})$$

$$\mathbf{r}(0) = \mathbf{r}_0 = 0$$

- AS, linear and decoupled residual dynamics
- No initial transient, only excited by collisions

- No additional sensors (sensorless)
- No inertia matrix inversion
- No joint acceleration estimation

Residual dynamics - 2

$$\dot{\mathbf{r}} = \mathbf{K}_{\mathrm{o}}(\boldsymbol{\tau}_{\mathrm{k}} - \mathbf{r})$$

$\boldsymbol{\tau}_k$ not available for implementation: using robot model

$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{c}(\mathbf{q}, \dot{\mathbf{q}}) + \mathbf{g}(\mathbf{q}) + \boldsymbol{\tau}_{\mathrm{f}} = \boldsymbol{\tau}_{\mathrm{m}} + \boldsymbol{\tau}_{\mathrm{k}}$$

it is obtained

$$\dot{\mathbf{r}} = \mathbf{K}_{\mathrm{o}}(\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{c}(\mathbf{q}, \dot{\mathbf{q}}) + \mathbf{g}(\mathbf{q}) + \boldsymbol{\tau}_{\mathrm{f}} - \boldsymbol{\tau}_{\mathrm{m}} - \mathbf{r})$$

Residual dynamics - 3

$$\dot{\mathbf{r}} = \mathbf{K_o}(\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{c}(\mathbf{q}, \dot{\mathbf{q}}) + \mathbf{g}(\mathbf{q}) + \boldsymbol{\tau}_\mathbf{f} - \boldsymbol{\tau}_\mathbf{m} - \mathbf{r})$$

Joint acceleration estimation required:
introducing robot generalized momentum

$$\mathbf{p} = \mathbf{M}(\mathbf{q})\dot{\mathbf{q}}$$

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

it is obtained

$$\dot{\mathbf{r}} = \mathbf{K_o}(\dot{\mathbf{p}} - \dot{\mathbf{M}}(\mathbf{q})\dot{\mathbf{q}} + \mathbf{c}(\mathbf{q}, \dot{\mathbf{q}}) + \mathbf{g}(\mathbf{q}) + \boldsymbol{\tau}_\mathbf{f} - \boldsymbol{\tau}_\mathbf{m} - \mathbf{r})$$

Residual dynamics - 4

$$\dot{\mathbf{r}} = \mathbf{K}_o(\dot{\mathbf{p}} - \dot{\mathbf{M}}(\mathbf{q})\dot{\mathbf{q}} + \mathbf{c}(\mathbf{q},\dot{\mathbf{q}}) + \mathbf{g}(\mathbf{q}) + \boldsymbol{\tau}_f - \boldsymbol{\tau}_m - \mathbf{r})$$

Defining for compactness

$$\boldsymbol{\beta}(\mathbf{q},\dot{\mathbf{q}}) := \mathbf{c}(\mathbf{q},\dot{\mathbf{q}}) + \mathbf{g}(\mathbf{q}) + \boldsymbol{\tau}_f - \dot{\mathbf{M}}(\mathbf{q})\dot{\mathbf{q}}$$

$$\hat{\dot{\mathbf{p}}} := \mathbf{r} - \boldsymbol{\beta}(\mathbf{q},\dot{\mathbf{q}}) + \boldsymbol{\tau}_m$$

it is obtained

$$\dot{\mathbf{r}} = \mathbf{K}_o(\dot{\mathbf{p}} - \hat{\dot{\mathbf{p}}})$$

Residual dynamics - 5

$$\dot{\mathrm{r}} = \mathrm{K_o}(\dot{\mathrm{p}} - \hat{\dot{\mathrm{p}}})$$

$\dot{\mathrm{p}}$ not available for implementation: applying integral operator

$$\hat{\mathrm{p}} = \int_0^t (\mathrm{r} - \boldsymbol{\beta}(\mathrm{q}, \dot{\mathrm{q}}) + \boldsymbol{\tau}_{\mathrm{m}})\mathrm{dt}$$

it is obtained

$$\mathrm{r} = \mathrm{K_o}(\mathrm{p} - \mathrm{p_0} - \hat{\mathrm{p}})$$

Collision detection

$$\dot{\mathbf{r}} = \mathbf{K_o}(\boldsymbol{\tau}_\mathbf{k} - \mathbf{r})$$

- Residuals: excited iff a collision happens
- Monitoring signal: norm of the residual vector
- Threshold to balance false negatives and false positives

Contact link isolation

Jacobian on link i: no dependence on joints i+1 to n

$$\mathbf{J_c}(\mathbf{q}) = \left[* * * | \mathbf{O} \right]$$

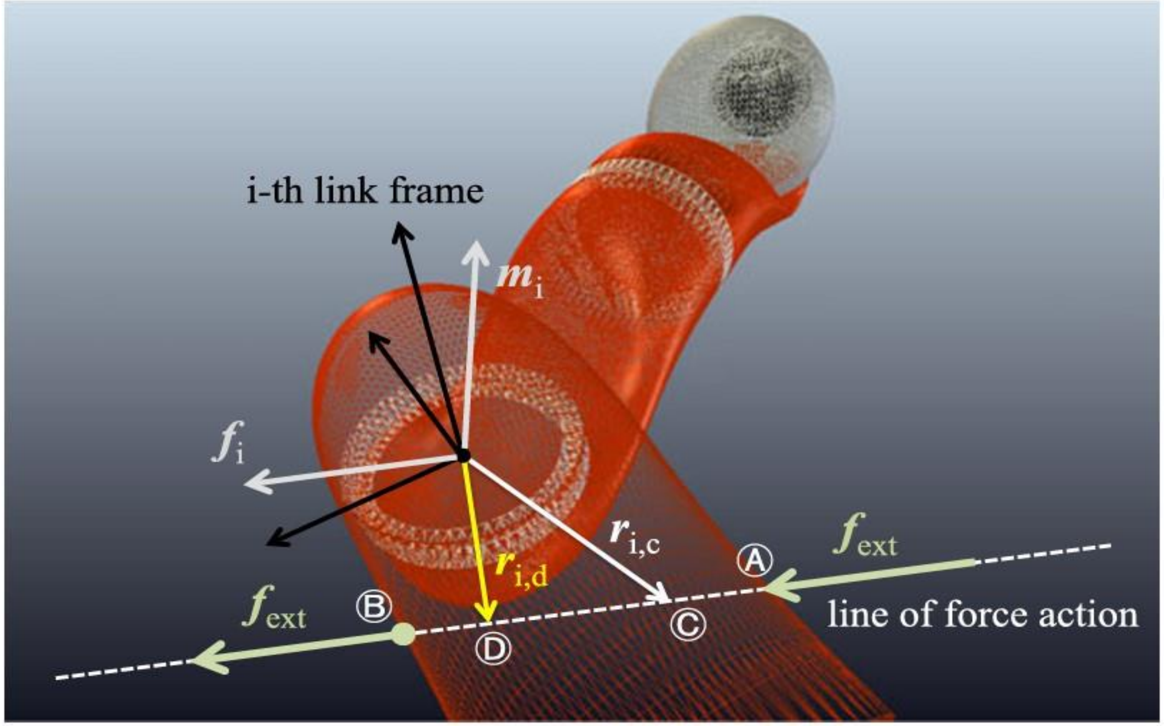
Collision on link i: no effect on residuals i+1 to n

$$\boldsymbol{\tau}_\mathbf{k} = \mathbf{J_c^T}(\mathbf{q}) \mathcal{F}_{ext}$$

$$i_c = max\{i \in \{1, ..., n\} : r_i \neq 0\}$$

Contact point isolation

Transformation between contact point and origin of frame i



$$\mathcal{F}_i = \mathbf{J}_{\mathbf{c,i}}^{\mathbf{T}} \mathcal{F}_{ext}$$

$$\mathbf{J}_{\mathbf{c}}(\mathbf{q}) = \mathbf{J}_{\mathbf{c,i}} \mathbf{J}_{\mathbf{i}}(\mathbf{q})$$

$$\mathbf{J}_{\mathbf{c,i}} = \begin{bmatrix} \mathbf{I}_{\mathbf{3x3}} & -\mathbf{S}(^0\mathbf{r}_{\mathbf{i,c}}) \\ \mathbf{O}_{\mathbf{3x3}} & \mathbf{I}_{\mathbf{3x3}} \end{bmatrix}$$

Contact point isolation

$\mathbf{r}$ estimator for τ_k for $\mathrm{K_o}$ big enough

$$\hat{\mathcal{F}}_i = (\mathbf{J}_{\mathrm{i}}^{\mathbf{T}}(\mathbf{q}))^{\#}\mathbf{r}$$

$$\mathcal{F}_{ext} = \begin{bmatrix} \mathbf{f_{ext}} \\ \mathbf{0_{3x1}} \end{bmatrix}$$

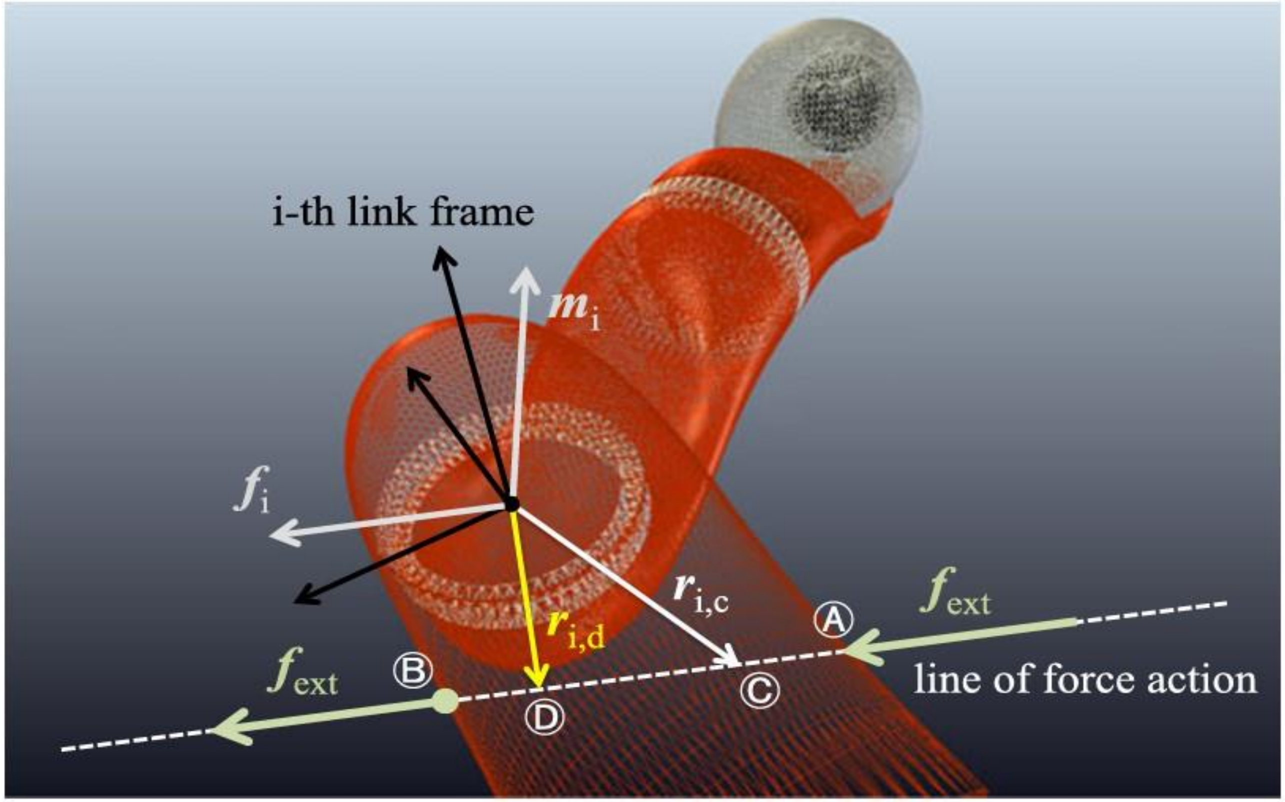
From the force transformation:

$$\hat{\mathcal{F}}_i = \begin{bmatrix} \hat{\mathbf{f}}_i \\ \hat{\mathbf{m}}_i \end{bmatrix} = \begin{bmatrix} \mathbf{I_{3x3}} & \mathbf{O_{3x3}} \\ -\mathbf{S^T}({}^0\mathbf{r_{i,c}}) & \mathbf{I_{3x3}} \end{bmatrix} \begin{bmatrix} \mathbf{f_{ext}} \\ \mathbf{0_{3x1}} \end{bmatrix}$$

$$\hat{\mathbf{m}}_i = \mathbf{S^T}(\hat{\mathbf{f}}_{\mathrm{i}})\,{}^0\mathbf{r_{i,c}}$$

Contact point isolation

$$\hat{\mathbf{m}}_i = \mathbf{S}^{\mathrm{T}}(\hat{\mathbf{f}}_{\mathrm{i}})\,{}^{0}\mathbf{r}_{\mathrm{i,c}}$$



Rank = 2
Solution: subspace of dimension 1

$${}^{0}\mathbf{r}_{\mathrm{i,d}} = \left(\mathbf{S}^{\mathrm{T}}(\hat{\mathbf{f}}_{\mathrm{i}})\right)^{\#}\hat{\mathbf{m}}_{\mathrm{i}}$$

$${}^{0}\mathbf{r}_{\mathrm{i,c}} = {}^{0}\mathbf{r}_{\mathrm{i,d}} + \lambda\frac{\hat{\mathbf{f}}_{\mathrm{i}}}{||\hat{\mathbf{f}}_{\mathrm{i}}||}$$

Contact wrench identification

Contact point Jacobian is now known

$$\boldsymbol{\tau}_{\mathbf{k}} = \mathbf{J}_{\mathbf{c}}^{\mathbf{T}}(\mathbf{q})\mathcal{F}_{ext}$$

$\mathbf{r}$ estimator for τ_k for $\mathrm{K_o}$ big enough

$$\hat{\mathcal{F}}_{ext} = (\mathbf{J}_{\mathbf{c}}^{\mathbf{T}}(\mathbf{q}))^{\#}\mathbf{r}$$

Limits of the residual method

- Compromise for $\mathbf{K_o}$
  - small $\mathbf{K_o}$ to limit initial transient
  - big $\mathbf{K_o}$ to have τ_k estimated by $\mathbf{r}$

- Collision detectable iff produce work
- Jacobian not full rank for i<6 or in singularities

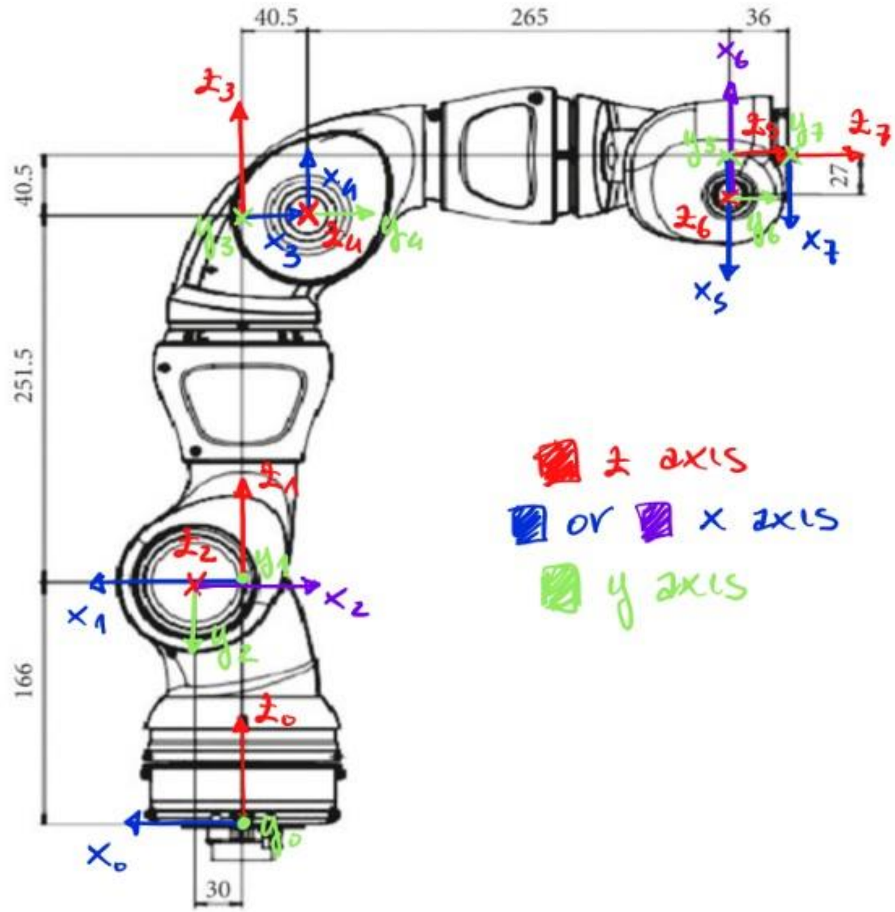
- Requires model knowledge (model-based)

Kinematic and dynamic model of the ABB YuMi robot

Model

- The dynamic model is generated using the software openSYMORO, using Newton-Euler algorithm
- openSYMORO requires the use of the modified DH convention
- Generated code leads to faster simulations than our custom NE implementation

Kinematic model



i	α_i [rad]	a_i [m]	d_i [m]	θ_i [rad]
1	0	0	0.166	q_1
2	$\pi/2$	0.03	0	q_2
3	$\pi/2$	0.03	0.2515	q_3
4	$-\pi/2$	0.0405	0	q_4
5	$-\pi/2$	0.0405	0.265	q_5
6	$-\pi/2$	0.027	0	q_6
7	$-\pi/2$	0.027	0.036	q_7

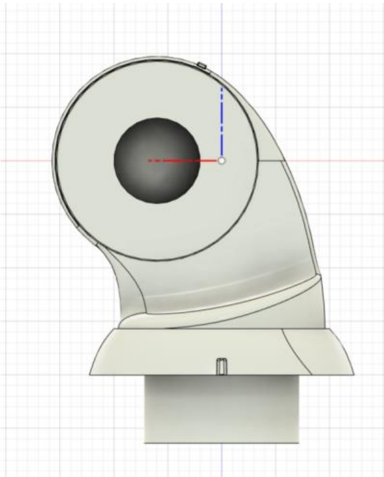
DHM table

$$\mathbf{q} = \begin{bmatrix} 0 & \pi & 0 & -\frac{\pi}{2} & \pi & \pi & \pi \end{bmatrix}^T$$

Dynamic model

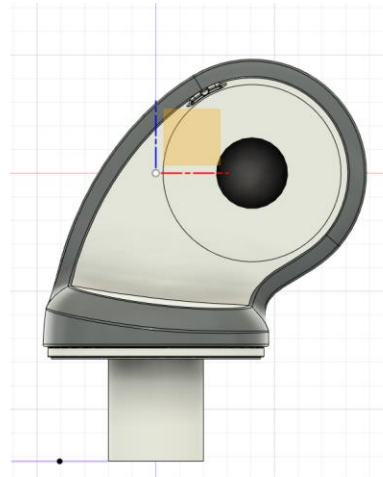
- Inertial parameters are obtained via CAD analysis in Autodesk Fusion 360
- 3D .step files are provided by ABB for each link
- In CAD links are matched to their DHM configuration
- Material is set to magnesium AZ63A, to match material (generic "magnesium alloy") and weight (9.5kg) mentioned in the product page

Links in CAD

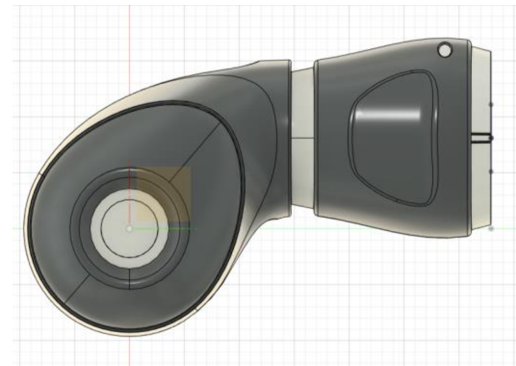


Link 1

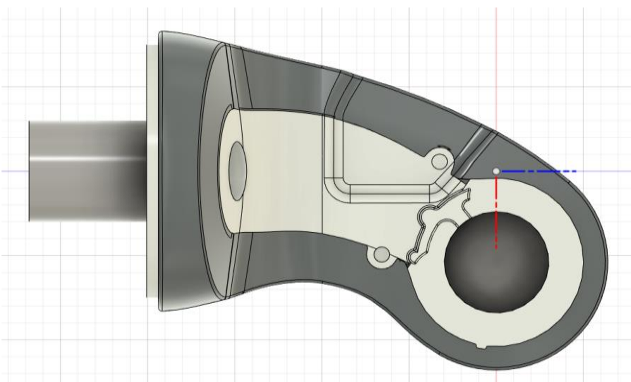
Link 2



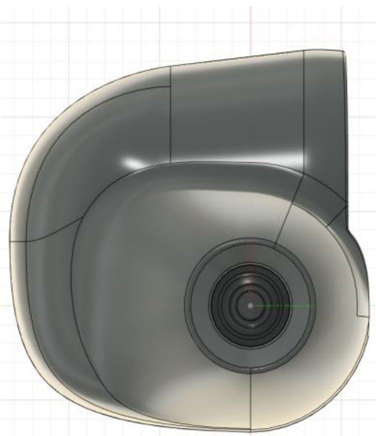
Link 3



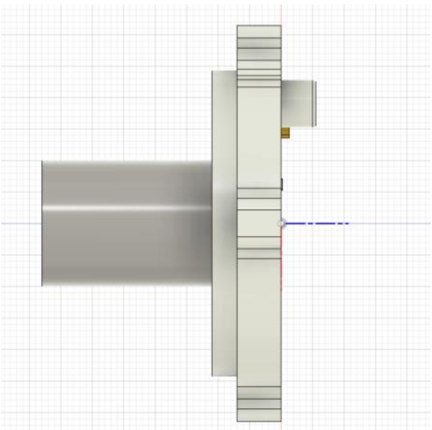
Link 4



Link 5



Link 6



Link 7

Dynamic model

Parameter	Link 1	Link 2	Link 3	Link 4	Link 5	Link 6	Link 7
m [kg]	1.761	2.577	1.408	2.158	0.628	0.859	0.056
CoM_x [m]	0.009	0.017	0.019	0.023	0.007	0.011	0
CoM_y [m]	-0.023	-0.063	0.026	0.056	0.027	-0.012	-0.001
CoM_z [m]	-0.05	-0.013	-0.035	-0.017	-0.054	-0.01	-0.011
XX [kg m^2]	0.011	0.024	0.007	0.017	0.004	0.001	$1.980 \cdot 10^{-5}$
XY [kg m^2]	0.001	0.005	-0.001	-0.005	0	0	≈ 0
XZ [kg m^2]	0	0	0	0	0	0	≈ 0
YY [kg m^2]	0.01	0.005	0.007	0.005	0.003	0.001	$1.971 \cdot 10^{-5}$
YZ [kg m^2]	0	0	0	0	0	0	≈ 0
ZZ [kg m^2]	0.004	0.024	0.004	0.017	0.001	0.001	$1.578 \cdot 10^{-5}$

Uncertain model

- Up to 20% uncertainty on dynamical parameters is considered
- Uncertainty is represented as a multiplicative constant on inertial parameters ranging from 0.8 to 1.2
- Three different costants for each link (21 in total), one each for
  - Elements of the inertia matrix
  - Center of mass
  - Mass

Implementation

- Code generated by openSYMORO is converted into MATLAB code for simulation. Functions for:
  - Inertia matrix M(q)
  - Nonlinear terms n(q,dq)
  - Jacobian of frame i J_i(q)
  - Gravity terms are obtained by g(q) = n(q, 0)

- Uncertainties are randomly generated with uniform distribution when simulation starts

Simulations on the ABB YuMi robot

General scheme

- Robot dynamics is simulated in continuous time with ode45
- Control and residual dynamics are computed in discrete time, 1ms sampling time
- Control uses a ZOH
- For residual:
  - Integral term approximated with Euler
  - Approximate derivative

$$\dot{\mathbf{M}}_{\mathbf{k}}(\mathbf{q}) \approx \frac{\mathbf{M}_{\mathbf{k}}(\mathbf{q}) - \mathbf{M}_{\mathbf{k-1}}(\mathbf{q})}{T_s}$$

Controller

- Feedback Linearization controller

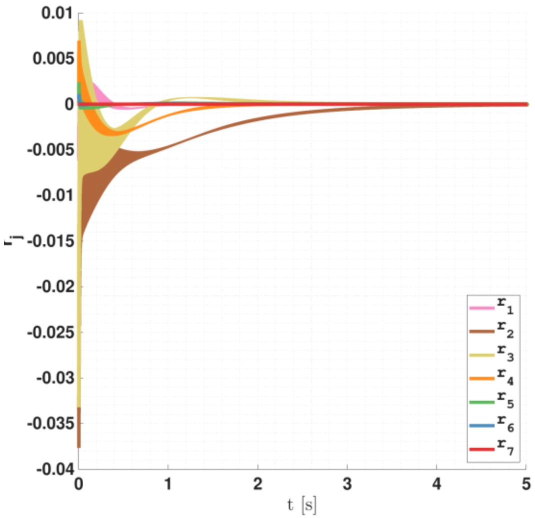
$$\boldsymbol{\tau}_{\mathbf{m}} = \hat{\mathbf{M}}(\mathbf{q})(\ddot{\mathbf{q}}_{\mathbf{d}} + \mathbf{K}_{\mathbf{p}}(\mathbf{q}_{\mathbf{d}} - \mathbf{q}) + \mathbf{K}_{\mathbf{d}}(\dot{\mathbf{q}}_{\mathbf{d}} - \dot{\mathbf{q}})) + \hat{\mathbf{n}}(\mathbf{q}, \dot{\mathbf{q}})$$

  - For regulation task

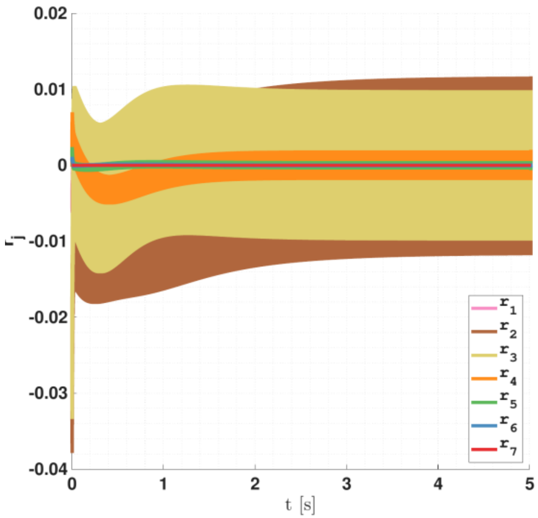
$$\boldsymbol{\tau}_{\mathbf{m}} = \hat{\mathbf{M}}(\mathbf{q})(\mathbf{K}_{\mathbf{p}}(\mathbf{q}_{\mathbf{d}} - \mathbf{q}) - \mathbf{K}_{\mathbf{d}}\dot{\mathbf{q}}) + \hat{\mathbf{n}}(\mathbf{q}, \dot{\mathbf{q}})$$

$$\mathbf{K}_{\mathbf{p}} = diag\{200\} \qquad \mathbf{K}_{\mathbf{d}} = diag\{200\}.$$

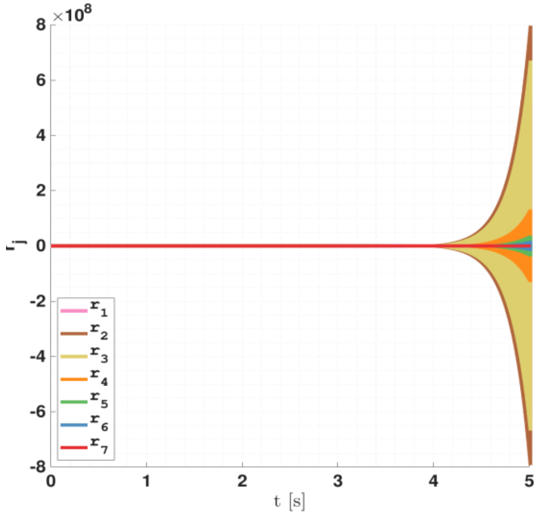
Ko tuning and stability of residual dynamics



$$K_o = 1995\ s^{-1}$$



$$K_o = 2000\ s^{-1}$$

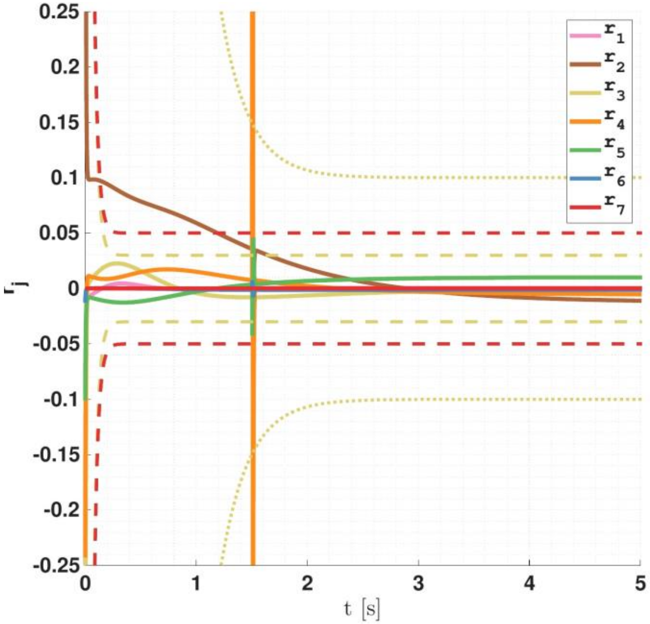


$$K_o = 2005\ s^{-1}$$

Final choice: $K_o = 1000\ s^{-1}$

Thresholds tuning

- Force modelling:
  $10N \leq ||f|| \leq 500N$
- Threshold:negative exponential for transient + steady state constant value
- Tuning with a force
  $||f|| = 10N$

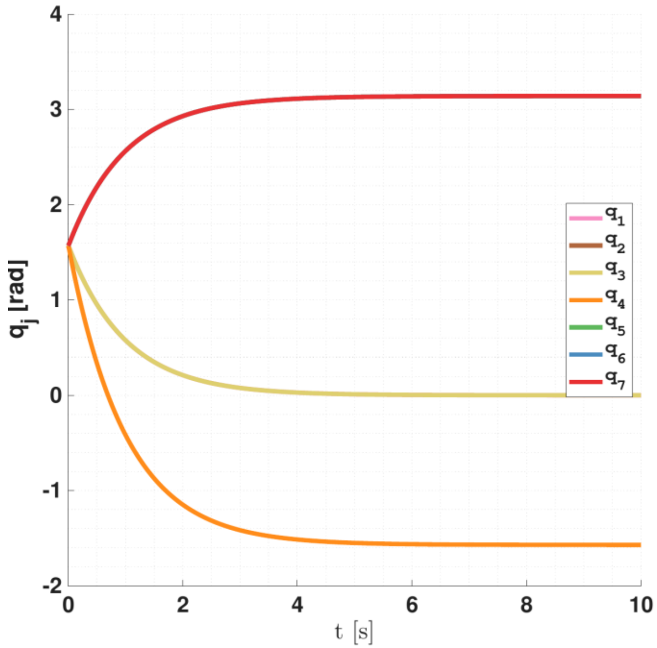


$$\epsilon_{nom} = \begin{bmatrix} 0.05 & 0.05 & 0.03 & 0.05 & 0.05 & 0.05 & 0.05 \end{bmatrix}^T \cdot e^{1-30t}$$

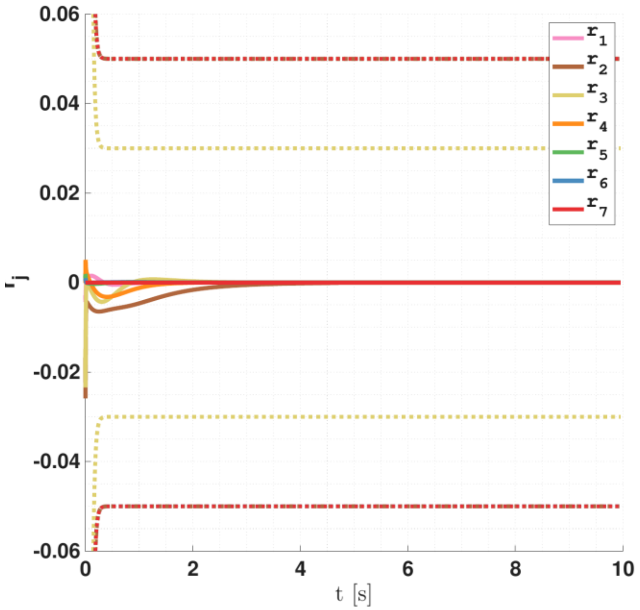
$$\epsilon_{unc} = \begin{bmatrix} 1 & 1.2 & 0.1 & 1 & 1 & 1 & 1 \end{bmatrix}^T \cdot e^{3-4t}$$

Task 1: regulation

- Desired (rest) position: $\mathbf{q_d} = \begin{bmatrix} 0 & \pi & 0 & -\frac{\pi}{2} & \pi & \pi & \pi \end{bmatrix}^T$
- Initial (rest) position: $\mathbf{q_0} = \begin{bmatrix} \frac{\pi}{2} & \frac{\pi}{2} & \frac{\pi}{2} & \frac{\pi}{2} & \frac{\pi}{2} & \frac{\pi}{2} & \frac{\pi}{2} \end{bmatrix}^T$

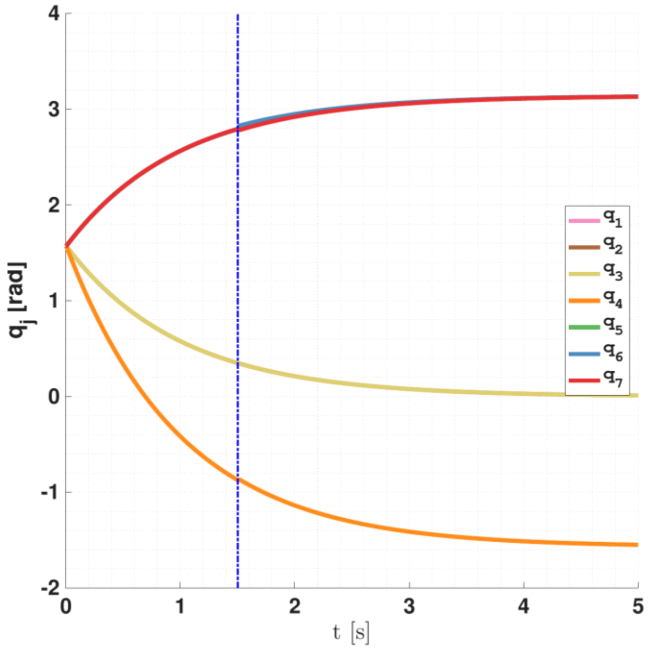


Joints

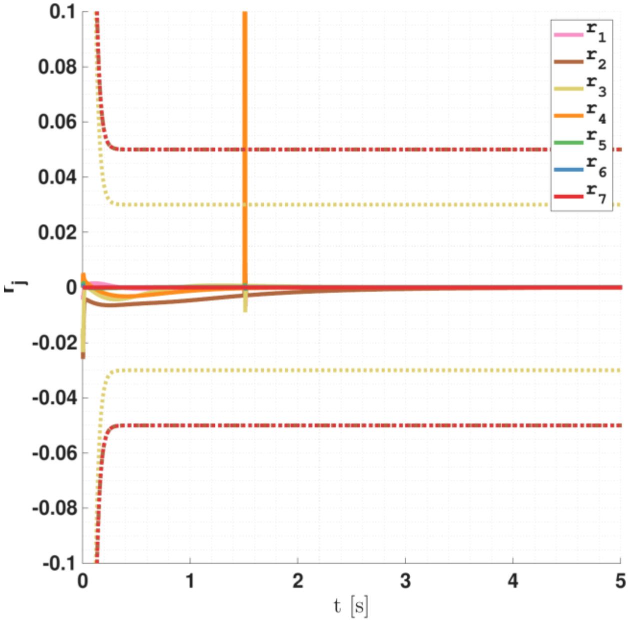


Residuals

Collision link 4 – 100 N (nominal case)



Joints



Residuals

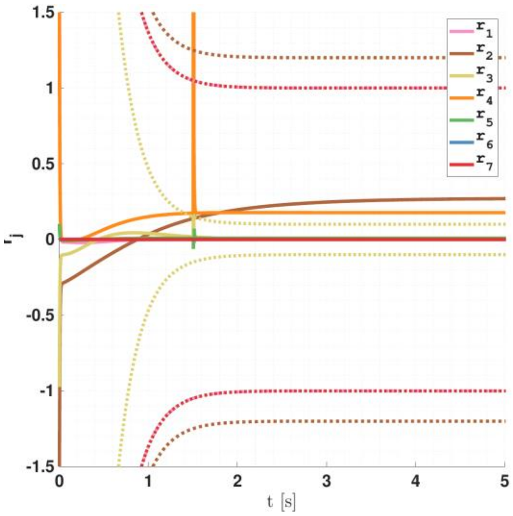
- Collision correctly detected on link 4 at t=1.501 s
- Isolation and identification not accurate ($\rho(J) = 4$)

$$ {}^{0}\mathbf{r}_{4,\mathbf{d}} = \begin{bmatrix} -0.0017 \\ -0.0007 \\ 0.0142 \end{bmatrix} \; \mathrm{m} $$

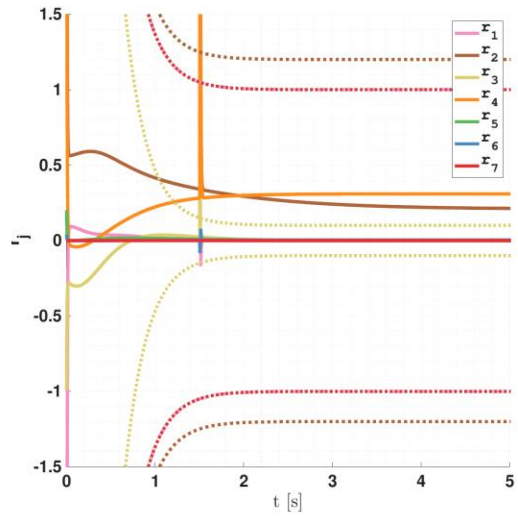
$$ \hat{\mathcal{F}}_{ext} = \begin{bmatrix} 59.3696 \\ 49.6715 \\ -4.8100 \\ 1.4515 \\ 1.2157 \\ -0.1168 \end{bmatrix} \; \begin{bmatrix} \mathrm{N} \\ \mathrm{Nm} \end{bmatrix} $$

Collision link 4 – 100 N (uncertain residuals)

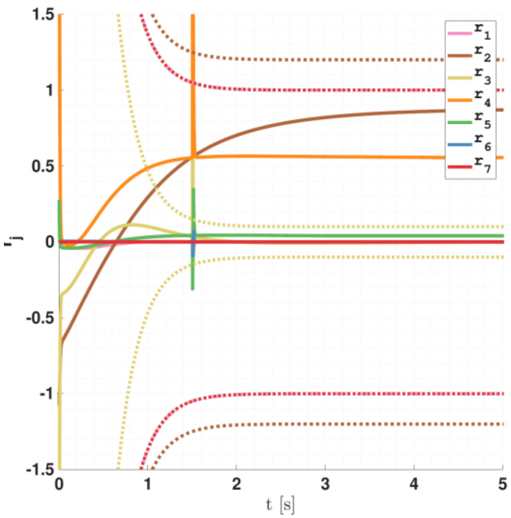
(0,5]%
uncertainty



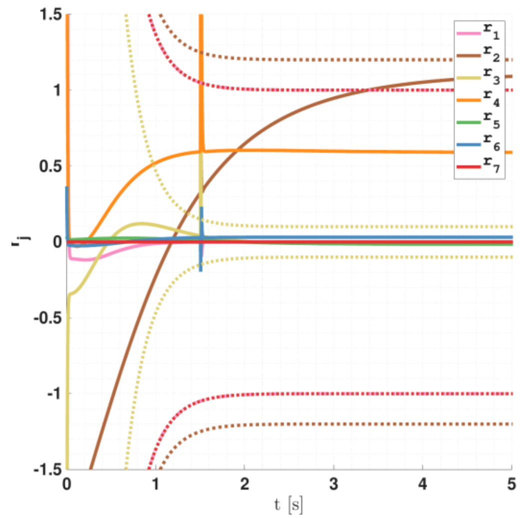
(5,10]%
uncertainty



(10, 15]%
uncertainty

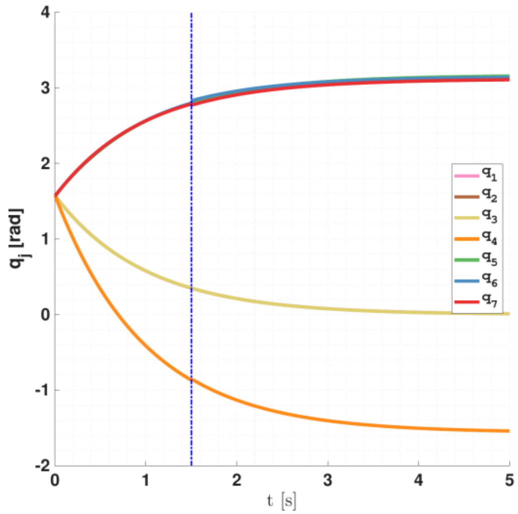


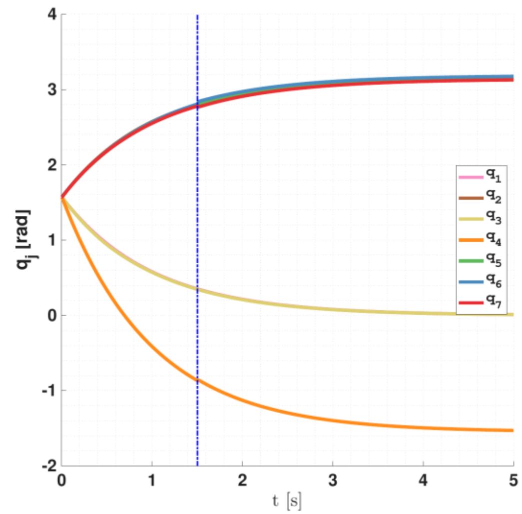
(15,20]%
uncertainty



Collision link 4 – 100 N (uncertain joints)

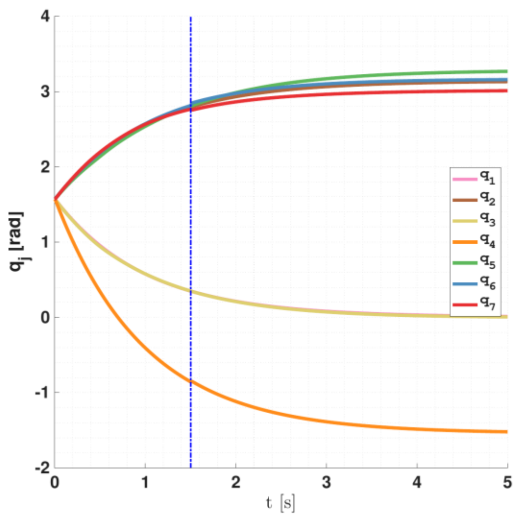
(0,5]%
uncertainty

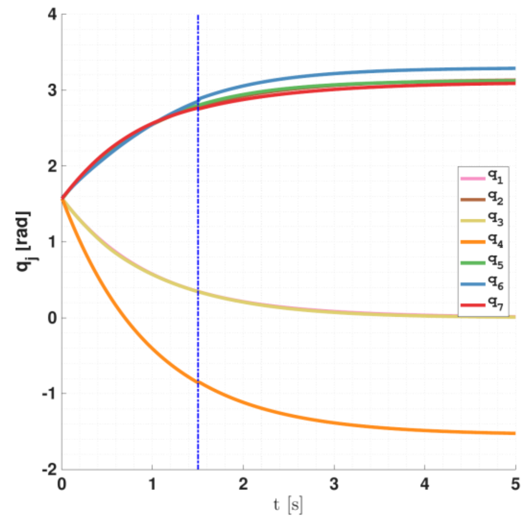




(5,10]%
uncertainty

(10, 15]%
uncertainty

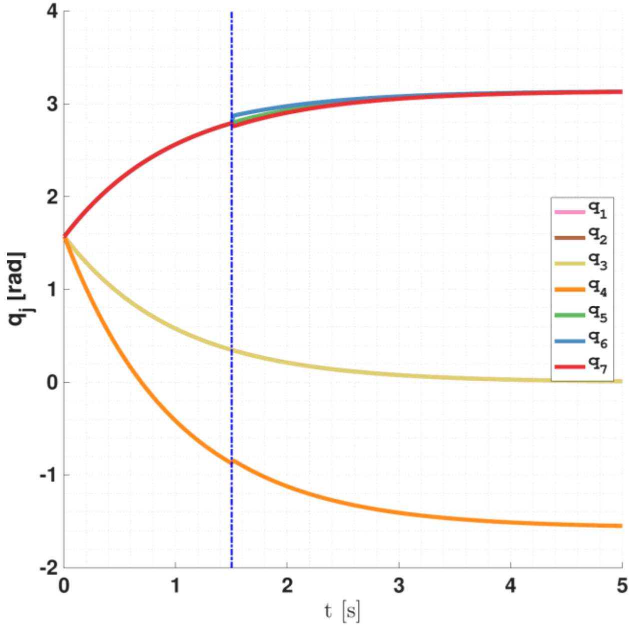




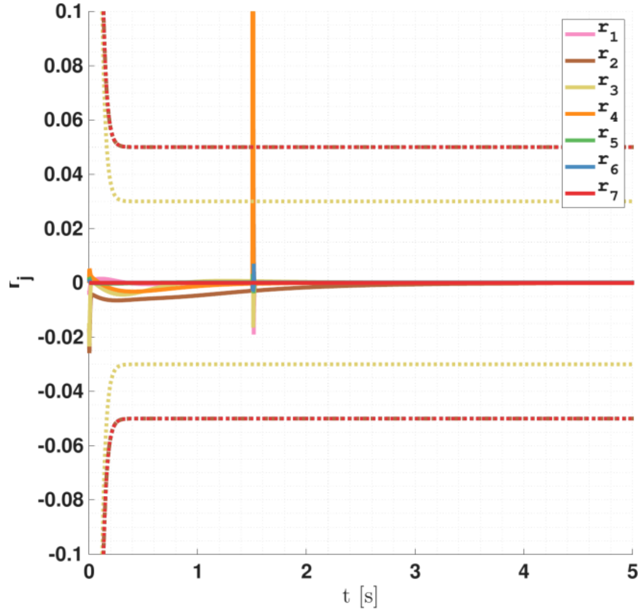
(15,20]%
uncertainty

Collision link 4 – 250 N (nominal case)

- Collision correctly detected at t=1.501s



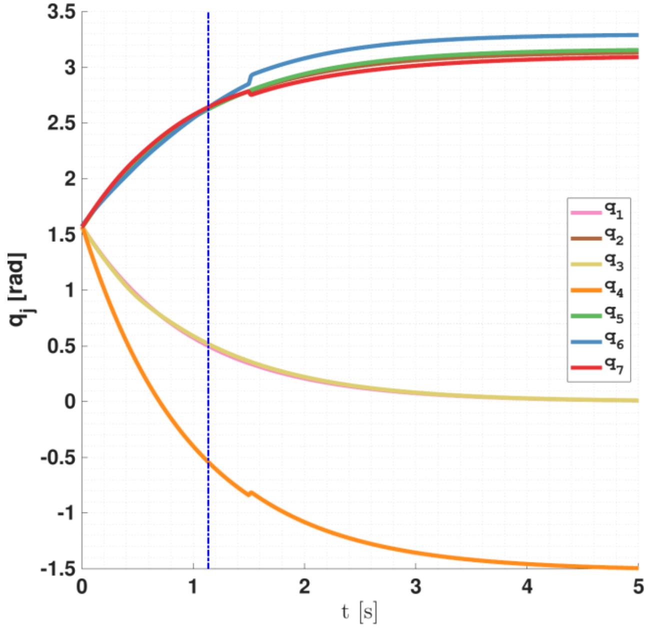
Joint



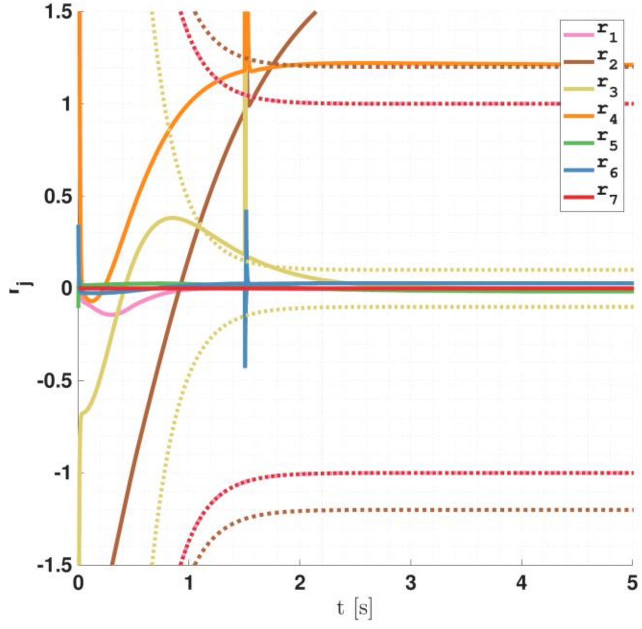
Residuals

Collision link 4 – 250 N

- Joints and residuals with (15,20]% uncertainty
- False positive on link 3 at t=1.137s



Joints



Residuals

Collision link 6 – off origin

- Collision force chosen to avoid huge changes in joint configuration
- Collision point simulated on outer shell of the link
- Expected isolation result is the minimum distance between the line of action of the force and origin of frame 6

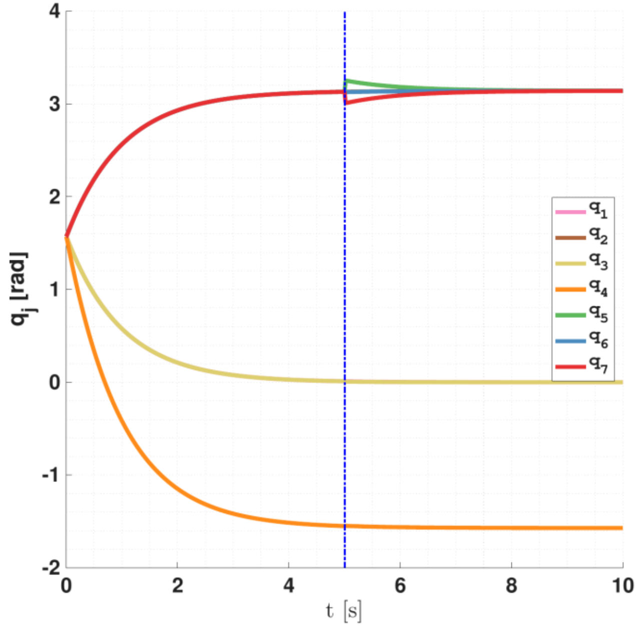
$$\mathcal{F}_{ext} = \begin{bmatrix} 0 \\ -10 \\ 0 \end{bmatrix} \text{ N}$$

$$^{0}\mathbf{r}_{\mathbf{6,c}} = \begin{bmatrix} 0.05 \\ 0.03 \\ 0 \end{bmatrix} \text{ m}$$

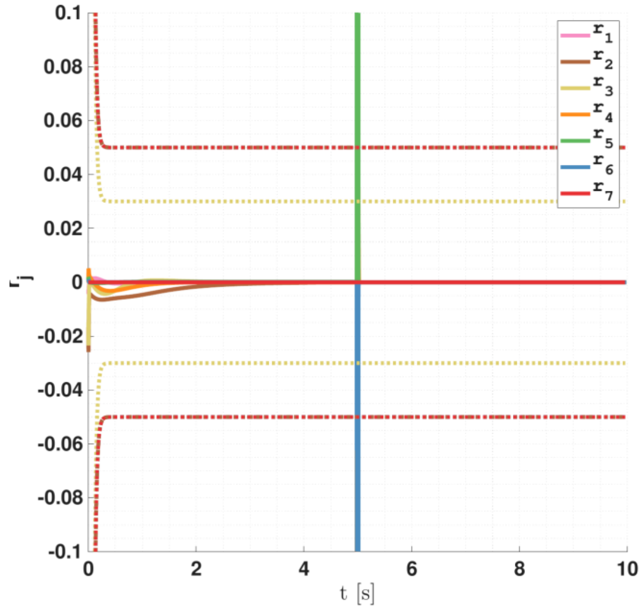
$$^{0}\mathbf{r}_{\mathbf{6,d}} = \begin{bmatrix} 0.05 \\ 0 \\ 0 \end{bmatrix} \text{ m}$$

Collision link 6 – off origin

- Nominal joints and residuals



Joints



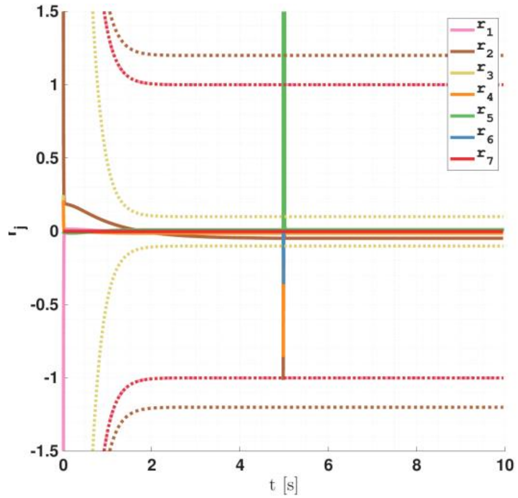
Residuals

Collision link 6 – off origin

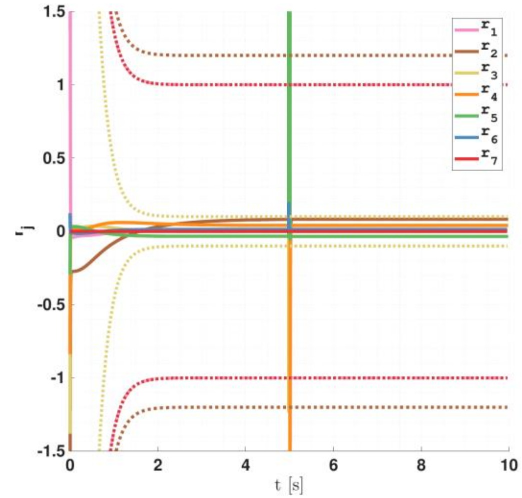
Uncertainty	Detection time [s]	Isolated link	Estimated point [m]	Estimated force [N]	Estimated momentum [Nm]
Nominal	5.001	6	$\begin{pmatrix} 0.0509 \\ 0 \\ -0.018 \end{pmatrix}$	$\begin{pmatrix} -0.0067 \\ -9.9626 \\ 0.0659 \end{pmatrix}$	$\begin{pmatrix} 0 \\ 0.0168 \\ -0.0001 \end{pmatrix}$
0%-5%	5.001	5	$\begin{pmatrix} 0.0434 \\ 0.0036 \\ 0.0008 \end{pmatrix}$	$\begin{pmatrix} 0.8180 \\ -9.7024 \\ 0.2118 \end{pmatrix}$	$\begin{pmatrix} -0.0939 \\ 1.1341 \\ -0.0300 \end{pmatrix}$
5%-10%	5.001	5	$\begin{pmatrix} 0.0825 \\ -0.0304 \\ 0.0693 \end{pmatrix}$	$\begin{pmatrix} -2.6560 \\ -9.2421 \\ -0.6377 \end{pmatrix}$	$\begin{pmatrix} -0.9510 \\ -3.4667 \\ -0.3740 \end{pmatrix}$
10%-15%	5.001	5	$\begin{pmatrix} -0.0818 \\ -0.0064 \\ 0.0291 \end{pmatrix}$	$\begin{pmatrix} 0.8110 \\ -9.5440 \\ 0.2171 \end{pmatrix}$	$\begin{pmatrix} -0.0266 \\ 0.3097 \\ -0.0065 \end{pmatrix}$
15%-20%	2.145	2	$\begin{pmatrix} -1.0409 \\ -0.1687 \\ -5.8336 \end{pmatrix}$	$\begin{pmatrix} -0.1862 \\ -0.0340 \\ 0.0342 \end{pmatrix}$	$\begin{pmatrix} -0.0057 \\ 0.0310 \\ 0.0001 \end{pmatrix}$

Collision link 6 – off origin (uncertain residuals)

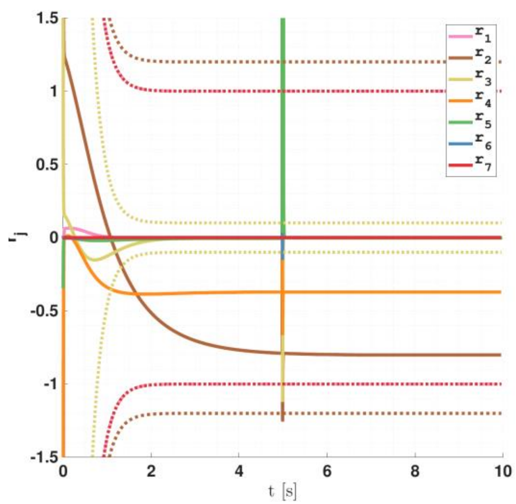
(0,5]%
uncertainty



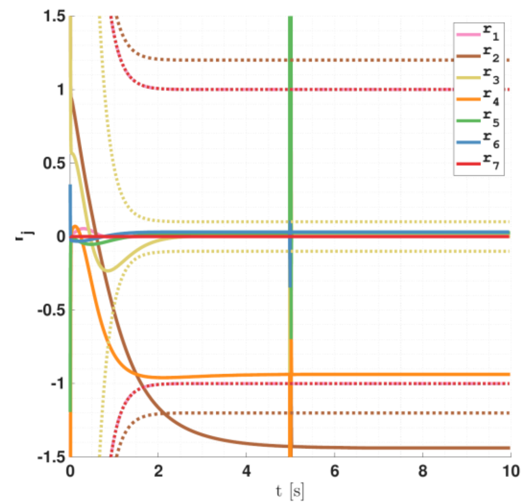
(5,10]%
uncertainty



(10, 15]%
uncertainty

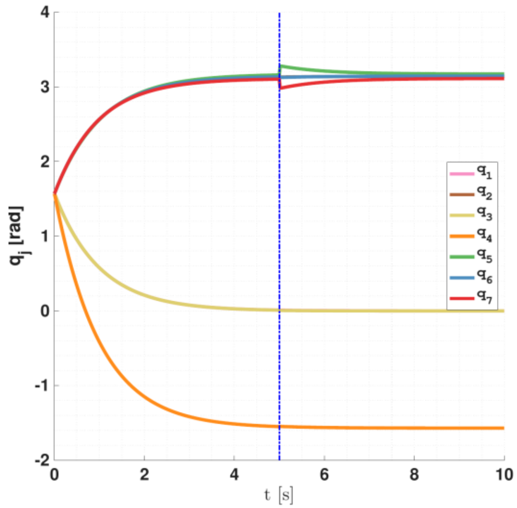


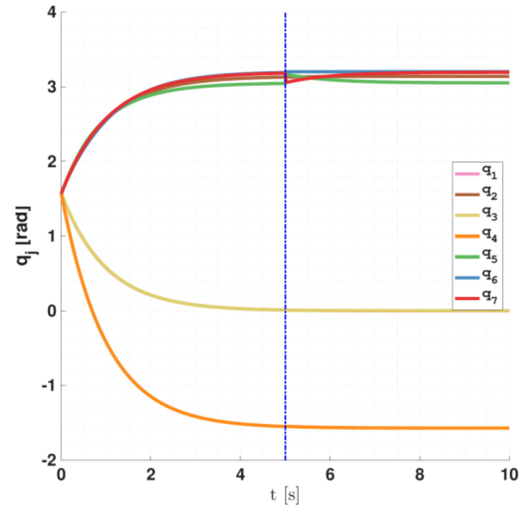
(15,20]%
uncertainty



Collision link 6 – off origin (uncertain joints)

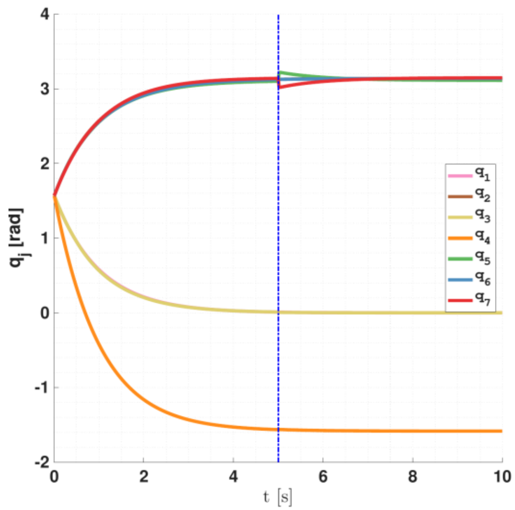
(0,5]%
uncertainty

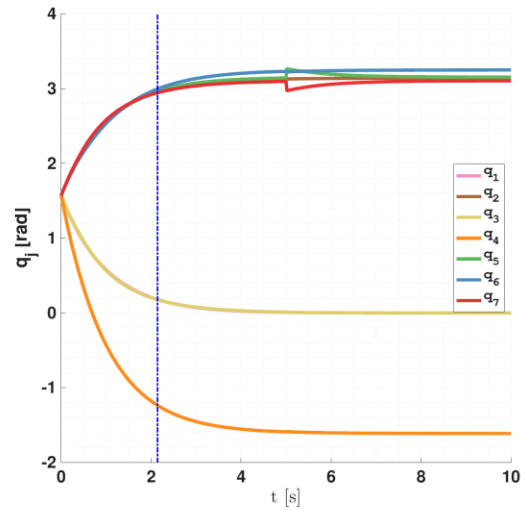




(5,10]%
uncertainty

(10, 15]%
uncertainty

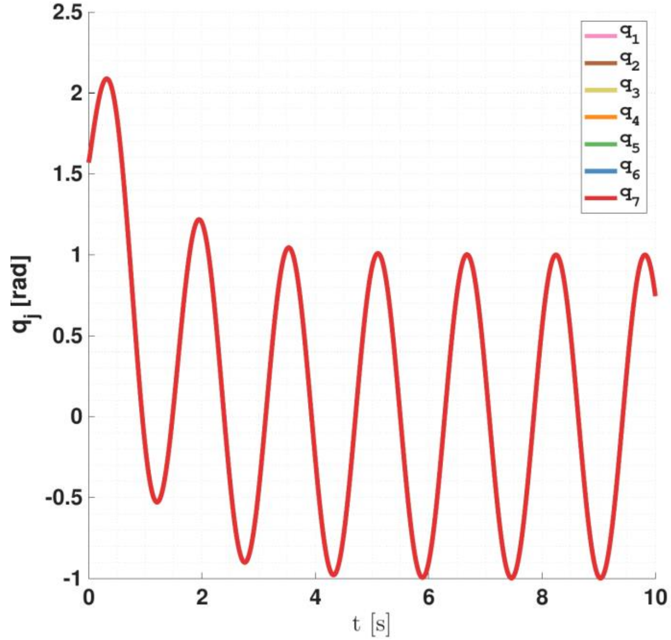




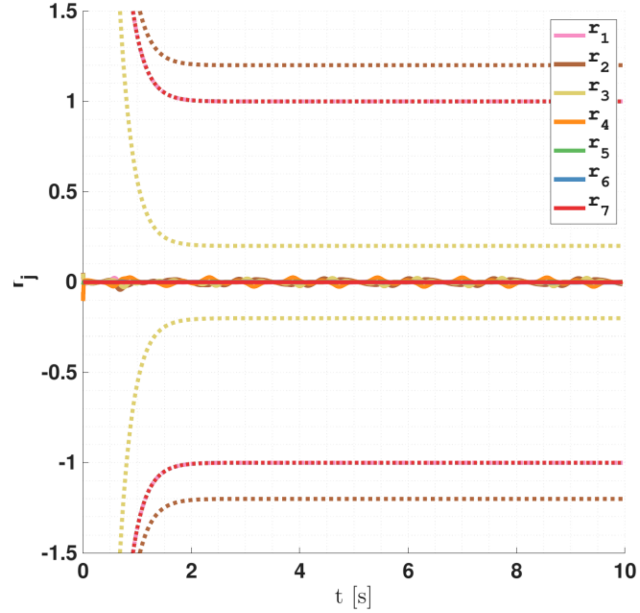
(15,20]%
uncertainty

Task 2: trajectory tracking

- Desired trajectory: $q_{d,i} = \sin(4t),\ \dot{q}_{d,i} = 4\cos(4t),\ \ddot{q}_{d,i} = -16\sin(4t)$
- Initial state: $\mathbf{q}_0 = \begin{bmatrix} \frac{\pi}{2} & \frac{\pi}{2} & \frac{\pi}{2} & \frac{\pi}{2} & \frac{\pi}{2} & \frac{\pi}{2} & \frac{\pi}{2} \end{bmatrix}^T$

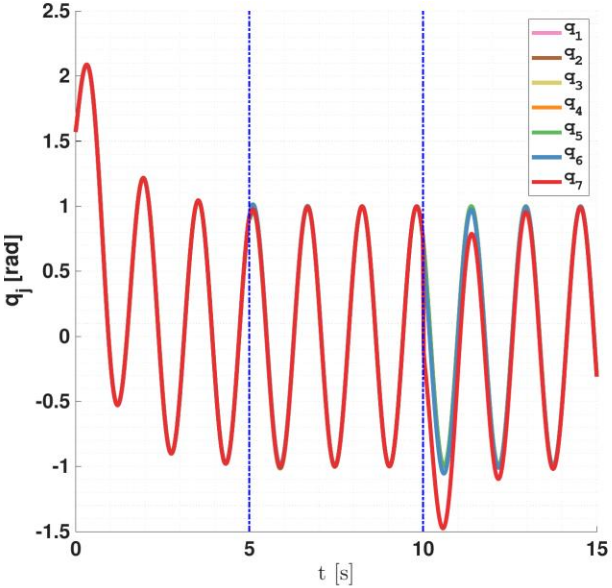


Joints

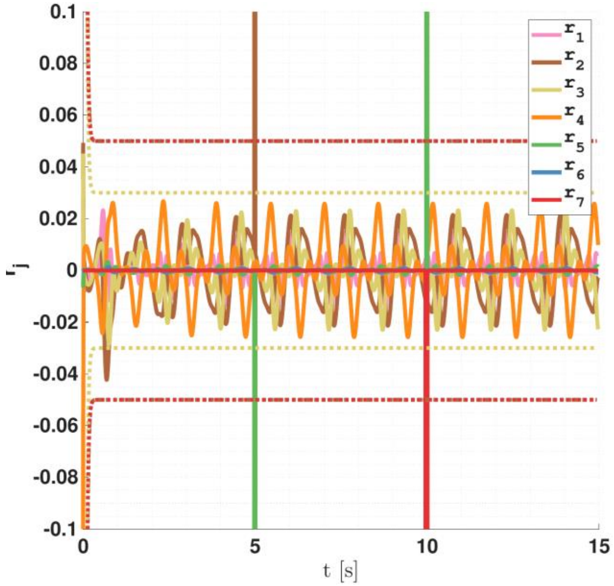


Residuals

Sequential collisions – link 5 and 7 (nominal case)



Joints



Residuals

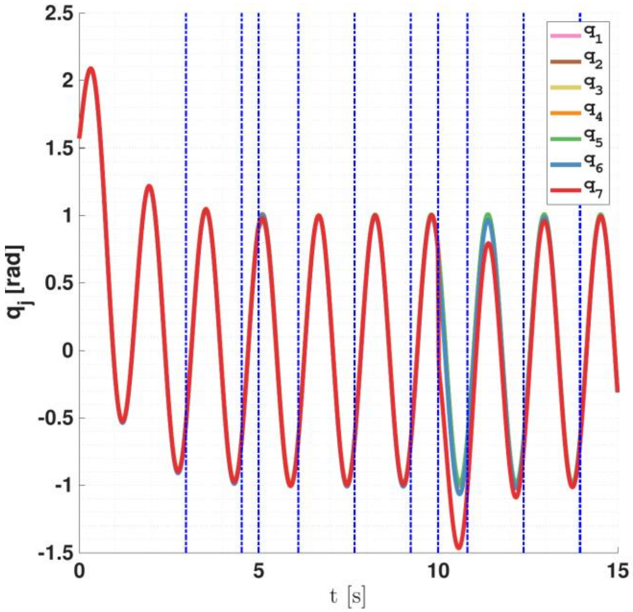
- Collisions correctly detected on link 5 at t=5.001s and on link 7 at t=10.001s
- Correct isolation and identification for link 7

$$ {}^{0}\mathbf{r}_{7,\mathbf{d}} = \begin{bmatrix} 7.372 \\ 2.457 \\ -9.657 \end{bmatrix} \cdot 10^{-4}\ \mathrm{m} $$

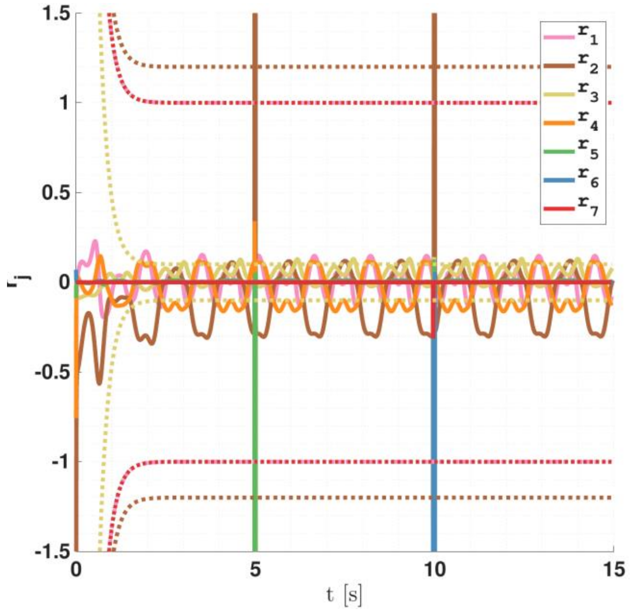
$$ \hat{\mathcal{F}}_{ext} = \begin{bmatrix} 9.8748 \\ 9.8512 \\ 10.0452 \\ 0.0014 \\ 0.0014 \\ 0.0014 \end{bmatrix} \begin{bmatrix} \mathrm{N} \\ \mathrm{Nm} \end{bmatrix} $$

Sequential collisions – link 5 and link 7

- False positives on link 3 with just (0,5]% uncertainty



Joints



Residuals

Conclusions

- Reliable method for collision monitoring
- Delay of 1 ms efficient for real time reactions
- Perfect behaviour in nominal case
- Performace deteriorates as uncertainty increases

Further developments:

- Friction and actuators inertia
- Control effort and actuators saturation

Thank you for the attention!