New Results on Fault and Collision Detection in Robot Manipulators

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Previous work: mainly with Raffaella Mattone, Sami Haddadin, Fabrizio Flacco†, Claudio Gaz

New results: include also joint work with Andrea Cristofaro, Claudio Gaz, Lorenzo Govoni, Pasquale Palumbo, Marco Pennese
Summary

Detection and isolation of fault events for different classes of robots

- actuator failures and link collisions in robots can both be handled as **system faults**
  - fault detection
  - ... and isolation (FDI)
  - identification of time profiles and classification of fault severity
- **review** of FDI results for robot manipulators with **rigid links** or with **elastic joints**
  - model-based residual methods
  - monitoring energy (only for detection) or generalized momentum (also for isolation)
  - without or with joint torque sensing
- **new results**
  - position-based residual for collisions in **rigid robots**
    - using a novel reduced-order observer for velocity (with experiments on KUKA LWR4 robot)
  - momentum-based residual for collisions in the general class of **robots with elastic joints**
    - with motor-link inertia couplings (Tomei model vs. Spong model)
  - residuals for actuator fault & collision in a **robot with a flexible link (Flexarm)**
    - detection and isolation results with full state measurements
    - detection using a nonlinear observer to estimate modal deformation variables and their rates
Rigid robots
Actuator faults – FDI

\[ M(q)\ddot{q} + c(q, \dot{q}) + g(q) + f(q, \dot{q}) = \tau + \tau_F \]

\[ p = M(q)\dot{q} \]

\[ \dot{p} = \tau + \tau_F - \alpha(q, \dot{q}) \]

\[ \alpha_i = -\frac{1}{2} \dot{q}^T \frac{\partial M}{\partial q_i} \dot{q} + g_i(q) + f_i(q_i, \dot{q}_i) \quad i = 1, \ldots, n \]

\[ r(t) = K_r \left( p - \int_0^t (\tau - \alpha(q, \dot{q}) + r) \, ds \right) \quad K_r > 0, \text{ diagonal} \]

\[ \dot{r} = K_r (\tau_F - r) \]

\[ \dot{r}_i = K_{r,i} (\tau_{F,i} - r_i) \quad i = 1, \ldots, n \]

A. De Luca, R. Mattone “Actuator failure detection and isolation using generalized momenta” ICRA 2003
Residual generator

Block diagram as a disturbance observer (first-order filtered estimate of $\tau_F$)

\[ \dot{p} = \tau - \alpha(q, \dot{q}) + K_r (p - \hat{p}) \]
\[ r = K_r (p - \hat{p}) \]
\[ e_{obs} = \tau_F - r \quad \Rightarrow \quad \dot{e}_{obs} = \dot{r}_F - K_r e_{obs} \sim -K_r e_{obs} \]

Initialization of integrators:
\[ \hat{p}(0) = p(0) \]
(zero if robot starts at rest)
Actuator FDI

Experimental results on a Pendubot (2R robot, underactuated)

- link 1 (actuated)
- link 2 (passive)

- one motor (joint 1), encoders at both joints
- motor 1 is driven by a sinusoidal voltage of period $2\pi$ sec (in open loop)
- bias fault on $\tau_1$ for $t \in [3 \div 4]$ s
- total fault on joint 2 for $t \in [3.5 \div 4.5]$ s
- fault concurrency for $t \in [3.5 \div 4]$ s

Pisa, January 12, 2023
Robot collision events
From coexistence to safe reaction and collaboration

Rigid robots

Link collisions – FDI

\[ M(q)\ddot{q} + S(q, \dot{q})\dot{q} + g(q) + f(q, \dot{q}) = \tau + \tau_C \]

Coriolis/centrifugal

friction

joint torques due to link collision (anywhere, any time)

\[ \dot{p} = \tau + \tau_C + S^T(q, \dot{q})\dot{q} - g(q) - f(q, \dot{q}) \]

skew-symmetric property in momentum dynamics

residual vector

\[ r(t) = K_r \left( p - \int_0^t (\tau + S^T(q, \dot{q})\dot{q} - g(q) - f(q, \dot{q}) + r) \, ds \right) \]

FDI property of the residual

\[ \dot{r} = K_r (\tau_C - r) \]

colliding link = largest index of residual component exceeding a detection threshold

A. De Luca, R. Mattone “Sensorless robot collision detection and hybrid force/motion control” ICRA 2005

A. De Luca, A. Albu-Schäffer, S. Haddadin, G. Hirzinger “Collision detection and safe reaction with the DLR-III lightweight manipulator arm” IROS 2006
Isolation of link collisions

Experiment with a position-controlled DLR LWR-III 7R robot while three links are in motion

Collision at link 4

Thresholds:
- $cd_1 = \text{off}$
- $cd_2 = \text{ON}$
- $cd_3 = \text{off}$
- $cd_4 = \text{ON}$
- $cd_5 = \text{off}$
- $cd_6 = \text{off}$
- $cd_7 = \text{off}$
Rigid robots
Link collisions – Detection only (but a simpler scalar residual)

\[
E = T + U_g = \frac{1}{2} \dot{q}^T M(q) \dot{q} + U_g(q)
\]

... and its dynamics

\[
\dot{E} = \dot{q}^T (\tau + \tau_C - f(q, \dot{q}))
\]

Scalar residual

\[
\sigma = k_\sigma \left( E - \int_0^t (\dot{q}^T (\tau - f(q, \dot{q})) + \sigma) \, ds \right)
\]

Detection only (and with robot in motion!)

\[
\dot{\sigma} = k_\sigma (\dot{q}^T \tau_C - \sigma)
\]

- scalar and vector residuals \( \sigma \) and \( \tau \) can be used together to improve thresholding performance in avoiding false positive or false negative collision events ...

A. De Luca, A. Albu-Schäffer, S. Haddadin, G. Hirzinger “Collision detection and safe reaction with the DLR-III lightweight manipulator arm” IROS 2006
Link collisions

Experiments on a Neura LARA 5 cobot (rigid model, no joint torque sensors)

D. Zurlo, T. Heitmann, M. Morlock, A. De Luca “Collision detection and contact point estimation using virtual joint torque sensing applied to a cobot” submitted to ICRA 2023
Sources of joint elasticity
Harmonic Drives in the DLR-KUKA LWR series of lightweight collaborative robots

\[ \tau_j = K(\theta - q) \]

- Harmonic Drives
- transmission belts and cables
- long shafts
- cycloidal gears
- Serial Elastic Actuators (SEA)
- Variable Stiffness Actuators (VSA)
Robots with elastic joints
Dynamic model and properties

\[ M(q)\ddot{q} + S(q, \dot{q})\dot{q} + g(q) = \tau_J + \tau_C \]

\[ M_m\ddot{\theta} + f_m(q, \dot{q}) + \tau_J = \tau \]

Motor friction

**Link equation**

\[ \tau_J = K(\theta - q) \]

Joint elastic torque

**Dynamic model (with Spong simplifying assumption)**

**Generalized momentum**

\[ p = \begin{pmatrix} p_q \\ p_\theta \end{pmatrix} = \begin{pmatrix} M(q)\dot{q} \\ M_m\dot{\theta} \end{pmatrix} \]

\[ p_q = M(q)\dot{q} \quad (= p \text{ of the rigid case}) \]

\[ \ddot{p}_\theta = \tau - \tau_J - f_m(q, \dot{q}) \]

**Total robot energy**

\[ E_{EJ} = T_q + T_m + U_g + U_e \]

\[ = \frac{1}{2} q^T M(q)\dot{q} + \frac{1}{2} \dot{\theta}^T M_m\dot{\theta} + U_g(q) + \frac{1}{2} (\theta - q)^T K(\theta - q) \]

\[ E_q = T_q + U_g \quad (= E \text{ of the rigid case}) \]

\[ \dot{E}_{EJ} = \dot{q}^T \tau_C + \dot{\theta}^T (\tau - f(q, \dot{q})) \]


Pisa, January 12, 2023
Robots with elastic joints

Link collisions – alternatives for vector and scalar residuals

\[ \mathbf{r}_{EJ}(t) = K_r \left( \mathbf{p}_q - \int_0^t (\tau_J + S^T(q, \dot{q}) \dot{q} - g(q) + r_{EJ}) \, ds \right) \]

\[ \dot{\mathbf{r}}_{EJ} = K_r (\tau_C - r_{EJ}) \]

FDI property

\[ \mathbf{r}_{EJ}(t) = K_r \left( \mathbf{p}_q - \int_0^t \left( K(\theta - q) + S^T(q, \dot{q}) \dot{q} - g(q) + r_{EJ} \right) \, ds \right) \]

\[ \dot{\mathbf{r}}_{EJ} = K_r (\tau_C - r_{EJ}) \]

no use of joint stiffness (good also for VSA!)

\[ \mathbf{r}_{EJ}(t) = K_r \left( \mathbf{p}_q + \mathbf{p}_\theta - \int_0^t \left( \tau + S^T(q, \dot{q}) \dot{q} - g(q) - f_m(q, \dot{q}) + r_{EJ} \right) \, ds \right) \]

no need of joint torque sensors (best for SEA!)

\[ \dot{\mathbf{r}}_{EJ} = K_r (\dot{q}^T \tau_C - \sigma_{EJ}) \]

detection only

(with robot in motion)

S. Haddadin, A. Albu-Schäffer, A. De Luca, G. Hirzinger “Collision detection and reaction: A contribution to safe physical human-robot interaction” IROS 2008 (Best Application Paper Award)


Pisa, January 12, 2023
Collision detection and reaction
Portfolio of possible robot behaviors implemented on different systems (5 videos)

the early days (2005-08) ...

IROS 2016 (KUKA LWR4)

Mechatronics 2018 (UR 10)

I-RIM 2021 (KUKA KR5)

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May 2017

Dynamic Identification and Collision Detection/Isolation of Robots From Motor Currents/Torques with Unknown Signs
Claudio Gaz, Marco Pennese, Marco Capotondi, Valerio Modugno, Alessandro De Luca
Robotics Lab, DIAG
Sapienza Università di Roma
March 2022

Pisa, January 12, 2023
Reduced-order velocity observer for rigid robots

- to be used in output feedback control laws and for collision detection/isolation
- nice to have the same first-order structure of momentum-based residual
- should work in closed-loop or open-loop mode (with possibly unbounded velocity)

\[
\begin{align*}
M(q)\dot{z} &= \tau - S(q, \dot{q}) \dot{\hat{q}} - g(q) - f(q, \dot{q}) - k_0 M(q)\dot{\hat{q}} \\
\dot{\hat{q}} &= z + k_0 q
\end{align*}
\]

Theorem 1. Assume that $\|\dot{q}\| \leq v_{\text{max}}$ is known. Then, for any fixed $\eta > 0$, by choosing
\[
k_0 \geq (c_0 v_{\text{max}} + \eta) / \lambda_{\text{min}}(M(q))
\]
we obtain local exponential stability of the observation error $\epsilon = \dot{q} - \dot{\hat{q}}$ with a region of attraction $\mathcal{E}(\eta)$.

Theorem 2. Assume that $\limsup_{n\to\infty} ||\dot{q}|| \leq v$ exists but is yet unknown. Then, using a switching logic to adjust the gain with a hybrid dynamics scheme,
we obtain local exponential stability of the observation error $\epsilon = \dot{q} - \dot{\hat{q}}$.

A. Cristofaro, A. De Luca “Reduced-order observer design for robot manipulators” IEEE Control Systems Letters 2023 (online Nov 2022)
- **faster** convergence than with full-order observer (e.g., Nicosia-Tomei IEEE T-AC 1990)
- **robust** with respect to noisy measurements and model uncertainties

\[
\mathbf{\tau} = \mathbf{g}(\mathbf{q}) + \begin{pmatrix} \cos (t/2) \\ - \cos t \end{pmatrix}
\]
Use of position-based residual for collisions
Experiments on a KUKA LWR4 with momentum-based residual using the velocity observer

- numerical differentiation vs. observer
- 6 link collisions in sequence (over 30 s):
  L4 (twice, ±) ⇒ L5 (twice, ±) ⇒ L2 (twice, ±)
- both methods detect collisions correctly
- ND has two false isolations (#5 and #6)
- OBS isolates the colliding link correctly

only first 5 residuals are shown (out of 7)
Robots with elastic joints

A more complete dynamic model

- remove the extra modeling assumption by Spong (ASME Transactions JDSMC 1987)
  - include also the inertial couplings between motors and links
  - the additional terms become relevant only for low reduction ratios $n_{ri}$
    - structural property: the complete model is feedback linearizable only when allowing dynamic state feedback

\[ T_{m2} = \frac{1}{2} m_{r2} a_1^2 \dot{q}_1^2 + \frac{1}{2} I_{m2} \left( \dot{q}_1 + \dot{\theta}_{m2} \right)^2 \left[ \dot{\theta}_{m2} = n_{r2} \dot{\theta}_2 \right] \]

\[ = \frac{1}{2} \left( m_{r2} a_1^2 + I_{m2} \right) \dot{q}_1^2 + \frac{1}{2} \left( I_{m2} n_{r2}^2 \right) \dot{\theta}_2^2 + I_{m2} n_{r2} \dot{q}_1 \dot{\theta}_2 \]
Robots with elastic joints
Momentum-based residual for the complete model

- case of **constant** matrix $\mathbf{N}$ (e.g., all planar manipulators with $n$ revolute joints)

\[
\begin{pmatrix}
\mathbf{M}(q) & \mathbf{N} \\
\mathbf{N}^T & \mathbf{M}_m
\end{pmatrix}
\begin{pmatrix}
\ddot{q} \\
\dot{\theta}
\end{pmatrix}
+ \begin{pmatrix}
\mathbf{S}(q, \dot{q}) \dot{q} \\
0
\end{pmatrix}
+ \begin{pmatrix}
g(q) \\
\mathbf{f}_m(q, \dot{q})
\end{pmatrix}
= \begin{pmatrix}
\tau_C + \tau_J \\
\tau - \tau_J
\end{pmatrix}
\]

\[
\tau_J = \mathbf{K}(\theta - q)
\]

- addition of **constant** terms in the robot inertia matrix does not generate new velocity terms, based on Christoffel symbols computation

- **new** vector residual for collision detection and isolation

\[
\mathbf{r}_{EJ}(t) = \mathbf{K}_r \left( \mathbf{M}(q)\dot{q} + \mathbf{N}\dot{\theta} - \int_0^t (\tau_J + \mathbf{S}^T(q, \dot{q}) \dot{q} - g(q) + \mathbf{r}_{EJ}) \, ds \right)
\]

\[
\dot{\mathbf{r}}_{EJ} = \mathbf{K}_r (\mathbf{\tau}_C - \mathbf{r}_{EJ})
\]

$\mathbf{K}_r > 0$, diagonal
Robots with elastic joints

Momentum-based residual for the complete model

- **general** case of configuration-dependent matrix $N(q)$

$$\begin{pmatrix} M(q) & N(q) \\ N^T(q) & M_m \end{pmatrix} \begin{pmatrix} \ddot{q} \\ \dot{\theta} \end{pmatrix} + \begin{pmatrix} c_q(q, \dot{q}, \dot{\theta}) \\ c_\theta(q, \dot{q}) \end{pmatrix} + \begin{pmatrix} g(q) \\ f_m(q, \dot{q}) \end{pmatrix} = \begin{pmatrix} \tau_C + \tau_J \\ \tau - \tau_J \end{pmatrix}$$

Coriolis/centrifugal

- rotors of the motors are modeled as **balanced** uniform bodies (with center of mass on rotation axis) ⇒ the robot inertia matrix and the gravity vector are functions of link variables $q$ only

- dependencies in the **quadratic velocity terms** follow from Christoffel symbols (tedious) computations

$$c(q, \dot{q}) = \begin{pmatrix} c_q(q, \dot{q}, \dot{\theta}) \\ c_\theta(q, \dot{q}) \end{pmatrix} = \begin{pmatrix} S_{qq}(q, \dot{q}, \dot{\theta}) & S_{q\theta}(q, \dot{q}, \dot{\theta}) \\ S_{\theta q}(q, \dot{q}) & 0 \end{pmatrix} \begin{pmatrix} \dot{q} \\ \dot{\theta} \end{pmatrix} = S(q, \dot{q}, \dot{\theta}) \begin{pmatrix} \dot{q} \\ \dot{\theta} \end{pmatrix}$$

$$\mathcal{M}(q) = S(q, \dot{q}) + S^T(q, \dot{q})$$ extended skew-symmetry property

- **new** vector residual for collision detection and isolation

$$r_{EJ}(t) = K_r \left( M(q)\dot{q} + N(q)\dot{\theta} - \int_0^t \left( \tau_J + S_{qq}^T(q, \dot{q}, \dot{\theta})\dot{q} + S_{q\theta}^T(q, \dot{q})\dot{\theta} - g(q) + r_{EJ} \right) ds \right)$$

$$\dot{r}_{EJ} = K_r (\tau_C - r_{EJ})$$

$K_r > 0$, diagonal
Robots with flexible links
Motivating example: FLEXARM

- **FLEXARM** is a two-link planar direct-drive robot with revolute joints and a flexible forearm
  - the first link is very stiff, as opposed to the forearm
  - distributed flexibility is relevant only in the horizontal plane of motion (bending)
  - simple structure, but already with the most relevant nonlinear and coupling dynamic effects

- robot **state** (a finite-dimensional approximation!) can be measured by a combination of
  - motor encoders
  - optical sensors
  - strain gauges

@Sapienza Robotics Lab, 1990
A two-link robot with a flexible forearm

Relevant system variables

- **system variables**
  - **first rigid link**: joint angle $\theta_1$
  - **second flexible link**:
    - modeled as a bending Euler-Bernoulli beam with dynamic boundary conditions
    - distributed flexibility approximated with $n_e$ modal eigenfunctions $\phi_i$ and variables $\delta_i$
    
    $$w(s, t) = \sum_{i=1}^{n_e} \phi_i(s) \delta_i(t) = \phi^T(s) \delta(t) \quad s \in [0, \ell_2]$$

- joint angle $\theta_2$ pointing at the CoM of forearm

- **measurable quantities**
  
  $$\theta_c = \begin{pmatrix} \theta_{c1} \\ \theta_{c2} \end{pmatrix} = \begin{pmatrix} \theta_1 \\ \theta_2 + \sum_{i=1}^{n_e} \phi'_{i0} \delta_i \end{pmatrix}$$

  $$y_{\text{tip}} = \left( \theta_2 + \frac{w(\ell_2, t)}{\ell_2} \right) - \theta_{c2} = \sum_{i=1}^{n_e} \left( \frac{\phi_{ie}}{\ell_2} - \phi'_{i0} \right) \delta_i$$

  joint angles **clamped** to the motors (measured by **encoders**)

  **tip deflection** of the forearm (measured by an **optical sensor** at the link base)
A two-link robot with a flexible forearm

Dynamic model

**generalized coordinates**

\[ q = \begin{pmatrix} \theta \\ \delta \end{pmatrix} = (\theta_1, \theta_2, \delta_1, \ldots, \delta_{n_e})^T \in \mathbb{R}^{2+n_e} \]

**dynamic model**

\[ M(q)\ddot{q} + S(q, \dot{q})\dot{q} + K\delta + D\dot{\delta} = G\tau + \tau_F \]

**structure of terms**

\[ M(q) = \begin{pmatrix} M_{\theta\theta}(\theta_2, \delta) & M_{\theta\delta}(\theta_2) \\ M_{\theta\delta}^T(\theta_2) & I_{n_e \times n_e} \end{pmatrix} \quad S(q, \dot{q}) = \begin{pmatrix} S_{\theta\theta} & S_{\theta\delta} \\ S_{\delta\theta}^T & S_{\delta,\delta} \end{pmatrix} \]

due to modal normalization

\[ K = \begin{pmatrix} O_{2\times2} & O_{2\times n_e} \\ O_{n_e \times 2} & K_\delta \end{pmatrix} \quad D = \begin{pmatrix} O_{2\times2} & O_{2\times n_e} \\ O_{n_e \times 2} & D_\delta \end{pmatrix} \]

stiffness matrix

modal damping (+ joint viscous friction)

\[ G = \begin{pmatrix} I_{2\times2} \\ 0 \end{pmatrix} \]

input matrix

A. De Luca, L. Lanari, P. Lucibello, S. Panzieri, G. Ulivi “Control experiments on a two-link robot with a flexible forearm” CDC 1990
Actuator fault/collision detection and isolation

Momentum-based residuals for robots with flexible links

- **generalized momentum of a manipulator with flexible links**

\[
p = \begin{pmatrix} p_\theta \\ p_\delta \end{pmatrix} = \begin{pmatrix} M_{\theta\theta} \dot{\theta} + M_{\theta\delta} \dot{\delta} \\ M_{\delta\theta}^T \dot{\theta} + M_{\delta\delta} \dot{\delta} \end{pmatrix} = M(q) \dot{q}
\]

- **vector residual for actuator faults or collisions detection and isolation**

\[
r_\theta(t) = K_r \left( p_\theta - \int_0^t \left( \tau + S_{\theta\theta}^T \dot{\theta} + S_{\theta\delta}^T \dot{\delta} + r_\theta \right) ds \right) \in \mathbb{R}^2
\]

\[
\dot{r}_\theta = K_r (\tau_F - r_\theta)
\]

- ... a **complete** residual \( r \in \mathbb{R}^{2+n_e} \) could be designed, but \( r_\theta \) is already sufficient

- **threshold** condition for **detection** of an actuator fault/link collision event

\[
\exists i \in \{1, 2\} \quad \text{s.t.} \quad |r_i| \geq r_{th}
\]

- **usual rules for isolation** (= **index** of the largest/only component exceeding ...)

C. Gaz, A. Cristofaro, A. De Luca “Detection and isolation of actuator faults and collisions for a flexible robot arm” CDC 2020
Actuator faults
Simulation results (in all cases: under **PD control** for tracking sinusoidal joint trajectories)

- fault on motor 1: 90% of torque loss from $t_F = 5$ s
  - [Graphs showing outputs, torques, and residuals for motor 1 fault]

- fault on motor 2: 90% of torque loss from $t_F = 5$ s
  - [Graphs showing outputs, torques, and residuals for motor 2 fault]
- **concurrent** faults on both motors: 20% of torque loss for motor 1 from $t_{F1} = 5\, \text{s}$ and for motor 2 from $t_{F2} = 10\, \text{s}$

![Graphs showing outputs, torques, and residuals for actuator faults](image)

> it is always possible to **detect** and **isolate** the actuator faults
Link collisions
Simulation results

- collisions on both links
  - external force $F_C = (1 \ 1)^T$ applied to the end of the (rigid) link 1 for $t_{F1} \in [10, 12]$ s
  - external force $F_C = (1 \ 1)^T$ applied to the tip of the (flexible) link 2 for $t_{F2} \in [25, 27]$ s
  - relation from $F_C$ to $\tau_C$ with transpose of the contact Jacobian: $\tau_C = \tau_F = J_C^T(q)F_C$

\begin{itemize}
  \item outputs
  \item torques
  \item residuals
\end{itemize}

→ in most cases (!?), it is possible to \textbf{detect} and \textbf{isolate} the link collisions

→ ... but it is \textbf{not} possible to discriminate \textbf{actuator faults} from link collisions
Nonlinear state observer

General setup

- design of state observers for input-affine nonlinear system

\[ \dot{x} = f(x) + g(x)u \quad u \in \mathbb{R}^p, \; x \in \mathbb{R}^\nu, \; y \in \mathbb{R}^\mu \]

- (repeated) Lie derivatives of functions along a vector field

\[ L_f h_j(x) = \frac{\partial h_j}{\partial x} f(x) \quad L_f^k h_j(x) = L_f \left( L_f^{k-1} h_j(x) \right) \]

- compute the relative degree of each of the system (measurable) outputs

\[ \forall \; x \in \Omega \subseteq \mathbb{R}^\nu \quad L_g L_f^k h_j(x) = 0 \quad \forall k = 0, 1, \ldots, r_j - 2 \]

\[ \exists \; \bar{x} \in \Omega \subseteq \mathbb{R}^\nu : \quad L_g L_f^{r_j-1} h_j(\bar{x}) \neq 0 \]

- if the system has vector relative degree

\[ r = r_1 + \cdots + r_\mu = \nu \]

a Luenberger-type nonlinear state observer can be designed with local exponential convergence

see e.g. A. Isidori “Nonlinear Control Systems” 3rd Edition 1995
A drift-observability nonlinear observer

General setup

- when the system is **autonomous**, a drift-observability map having full rank could be found, which allows the design of a nonlinear state observer with similar convergence properties

\[
\Phi_j^T(x) = \begin{pmatrix} h_j(x) & L_f h_j(x) & \ldots & L_f^{\nu_j-1} h_j(x) \end{pmatrix}^T \in \mathbb{R}^{\nu_j}
\]

\[
J_\Phi(z) = \left. \frac{\partial \Phi}{\partial x} \right|_{x = \Phi^{-1}(z)} \quad \text{nonsingular} \quad \nu_1 + \cdots + \nu_\mu = \nu
\]


- if a vector relative degree **does not hold**, since the control input \( u \) is typically designed as \( u(x) \), one can look for and exploit a drift-like observability property

\[
\dot{x} = f(x) + g(x)u(x) = \tilde{f}(x) \quad \Rightarrow \quad \dot{x} = f(x) + g(x)u(\hat{x})
\]

\[
\Phi_j^T(x) = \begin{pmatrix} h_j(x) & L_f h_j(x) & \ldots & L_f^{\nu_j-1} h_j(x) \end{pmatrix}^T \in \mathbb{R}^{\nu_j}
\]

\[
J_\Phi(z) = \left. \frac{\partial \Phi}{\partial x} \right|_{x = \Phi^{-1}(z)} \quad \text{nonsingular} \quad \nu_1 + \cdots + \nu_\mu = \nu
\]

C. Gaz, A. Cristofaro, P. Palumbo, A. De Luca “A nonlinear observer for a flexible robot arm and its use in fault and collision detection” CDC 2022
Application of the drift-like observer to the FLEXARM

Synthesis procedure (for $n_e = 2$ modes)

inputs $\boldsymbol{u} = \boldsymbol{\tau} \in \mathbb{R}^2$, $\rho = 2$

measured outputs $\boldsymbol{y} = h(\boldsymbol{x}) \Rightarrow \boldsymbol{y} = \begin{pmatrix} \theta_1 \\ \theta_{c2} \\ y_{tip} \end{pmatrix} = h(\boldsymbol{q})$, $\mu = 3$

no vector relative degree $r = r_1 + r_2 + r_3 = 2 + 2 + 2 = 6 < 8 = \nu$

PD control with observed state(s)

$\boldsymbol{u} = \boldsymbol{u}(\hat{\boldsymbol{x}}) \Rightarrow \boldsymbol{\tau} = K_P (\theta_{c,des} - \theta_c) + K_D \begin{pmatrix} \dot{\theta}_{c,des} - \dot{\theta}_c \\ \dot{\theta}_1(q) \\ L_f \theta_1(\dot{q}) \\ L_f^2 \theta_1(q, \dot{q}) \\ \dot{\theta}_{c2}(q) \\ L_f \theta_{c2}(\dot{q}) \\ L_f^2 \theta_{c2}(q, \dot{q}) \\ y_{tip}(q) \\ L_f y_{tip}(\dot{q}) \end{pmatrix}^T$

$\nu_1 + \nu_2 + \nu_3 = 3 + 3 + 2 = 8 = \nu$, $\boldsymbol{J}_\Phi(\boldsymbol{z}) = \frac{\partial \Phi}{\partial \boldsymbol{x}} \bigg|_{\boldsymbol{x} = \Phi^{-1}(\boldsymbol{z})}$ nonsingular

nonlinear observer

$\hat{\boldsymbol{x}} = \boldsymbol{f}(\hat{\boldsymbol{x}}) + \boldsymbol{g}(\hat{\boldsymbol{x}})\boldsymbol{u}(\hat{\boldsymbol{x}}) + \boldsymbol{J}_\Phi^{-1}(\hat{\boldsymbol{x}})\Gamma(\boldsymbol{y} - h(\hat{\boldsymbol{x}}))$

C. Gaz, A. Cristofaro, P. Palumbo, A. De Luca “A nonlinear observer for a flexible robot arm and its use in fault and collision detection” CDC 2022
Dynamic feedback control

Simulation results: observer performance

- a PD law with observed velocity is applied to track the desired joint trajectories

\[
\begin{align*}
\theta_{c1, des}(t) &= 2 \sin 0.05\pi t \\
\theta_{c2, des}(t) &= 2 \sin 0.1\pi t
\end{align*}
\]

![Graphs showing observed and actual states, estimation and tracking errors](image)

estimation error convergence for the 8 states

tracking error convergence for the 3 outputs
Actuator fault detection

Simulation results: measurable observer error as monitoring signal

- an abrupt fault occurs for motor 1 at time \( t = 12 \) [s], with a 90% power loss

commanded/actual torques and controlled outputs
- contact force applied on link 1 from $t = 10$ to $12$ s and on link 2 from $t = 25$ to $27$ s

commanded/actual torques and controlled outputs

monitoring signal

$$\epsilon = (\theta_c - \hat{\theta}_c)^T (\theta_c - \hat{\theta}_c)$$
Conclusions

Take-home messages

- A physically-based residual approach (momentum/energy) to detect and isolate missing dynamic terms in robots (faults, collisions, unmodeled motor friction, ...)
  - Widely used in research and industry (DLR LWR/humanoids, KUKA iiwa, PAL Robotics, ...), often “rediscovered” in later papers under various forms (e.g., disturbance observer)
  - Applies equally well to different robotic systems – arms, UAVs (in contact!), humanoids – including manipulators with flexible elements (joints, links) and deformable soft robots!!
  - Exact (decoupled) FDI in mechanical systems: max # faults = # generalized coordinates

- Main application in safe physical Human-Robot Interaction (pHRI)
  - Localization of contact point(s) and identification of Cartesian collision/contact forces
    - Sometimes for free → combined with particle filters → using RGB-D or vision sensors
  - Classification problems
    - Distinguishing intentional contacts (for collaboration) from accidental collisions (fast reaction)
    - Severity of actuator faults (for on-line system reconfiguration)

- Being model-based, the main limitation is robustness to uncertainty
  - Requires good dynamic models – especially difficult is capturing friction in rigid robots
  - Combine multiple FDI approaches: model-based, signal-based, and isolation logics
  - Go adaptive? Use machine learning techniques?

Pisa, January 12, 2023
more papers [2004-17]

- A. De Luca, F. Flacco “Integrated control for pHRI: Collision avoidance, detection, reaction and collaboration” BioRob 2012 (Best Paper Award)
- E. Magrini, F. Flacco, A. De Luca “Estimation of contact forces using a virtual force sensor” IROS 2014
- E. Magrini, F. Flacco, A. De Luca “Control of generalized contact motion and force in physical human-robot interaction” ICRA 2015
- E. Magrini, A. De Luca “Hybrid force/velocity control for physical human-robot collaboration tasks” IROS 2016
- G. Buondonno, A. De Luca “Combining real and virtual sensors for measuring interaction forces and moments acting on a robot” IROS 2016
- E. Magrini, A. De Luca “Human-robot coexistence and contact handling with redundant robots” IROS 2017
... bibliography and video

Download pdf for personal use at www.diag.uniroma1.it/deluca/Publications

- more papers [2018-21]
  C. Gaz, E. Magrini, A. De Luca “A model-based residual approach for human-robot collaboration during manual polishing operations” Mechatronics 2018
  M. Iskandar, O. Eiberger, A. Albu-Schäffer, A. De Luca, A. Dietrich “Collision detection and localization for the DLR SARA robot with sensing redundancy” ICRA 2021
  M. Pennese, C. Gaz, M. Capotondi, V. Modugno, A. De Luca “Identification of robot dynamics from motor currents/torques with unknown signs,” I-RIM 2021 (Best Student Paper Award)

- videos
  F. Flacco, A. De Luca “Safe physical human-robot collaboration” IROS 2013 (Best Video Award Finalist)
  YouTube channel: RoboticsLabSapienza Playlist: Physical human-robot interaction

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Estimation of contact force

Sometimes, even **without** external sensing

- if contact is sufficiently “down” along the kinematic chain (≥ 6 residuals available), estimation of **pure contact forces** needs no external information ...

- a simple 3R planar case, with contact on different links; one can estimate:

  - only **normal** force to link, if contact point is known (1 informative residual signal)
    
    \[
    \text{rank } \{ J_{c1} \} = 1
    \]

  - full force on link, **even without** knowing contact (3 informative residuals)
    
    \[
    \text{rank } \{ J_{c3} \} = 2
    \]

  - full force on link, if contact point is known (2 informative residuals)
    
    \[
    \text{rank } \{ J_{c2} \} = 2
    \]
Collision or collaboration?

Distinguishing hard/accidental collisions and soft/intentional contacts

- using suitable low and high bandwidths for the residuals (first-order stable filters)
  \[ \dot{r} = -K_I r + K_I \tau_K \]
- a threshold is added to prevent false collision detection during robot motion

![Graph and diagram showing residual and time plots for collisions and soft contacts.]

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