Passivity-Based Control: Facing the Challenges of Modern Technology

Romeo Ortega

Laboratoire des Signaux et Systèmes

CNRS-CentraleSupelec

Gif-sur-Yvette, France

In collaboration with: S. Aranovskyi, A. Astolfi, P. Borja, F. Castaños, R. Cisneros, A. Donaire, P. Gandhi, E. Garcia, M. Hernandez, B. Jayawardana, F. Mancilla, J. Romero, R. Talj, M. Zhang, D. Zonetti.

Sharif University, Tehran, Iran, 15-16/04/2018

Layout

- Motivation and New Control Paradigm
- Passivity: The Key Articulating Concept
- Mathematical Formulation of Passivity-based Control (PBC)
- PID-PBC
- Applications

1. Motivation and New Control Paradigm

Control Challenges in the Modern World

- New engineering applications (including biomedical and others):
  - Strong coupling between subsystems.
  - Mutually interacting, instead of cause-effect, relations.
  - Need for accurate, nonlinear, non-isolated, models.
- Paradigmatic examples
  - Modern electrical (smart) grid
  - Interacting mechanical systems, *e.g.* teleoperators,...
  - Transportation systems
  - Bio-medical applications
  - $\vdots$
- Existing control theory, which adopts a signal-processing viewpoint, is inadequate to face those challenges.
- Objective: Provide a new control paradigm, based on considerations of energy, dissipation and interconnection.

Classical Control Theory

- Mathematical models are signal processors $u \mapsto y$

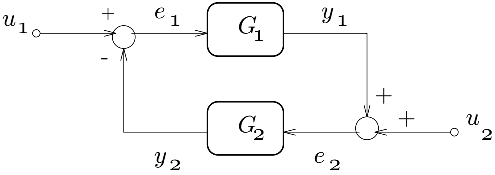
$$\dot{x} = f(x, u), \; y = h(x, u),$$

and analysis/design tools, *e.g.*, Lyapunov theory, not suitable to incorporate interconnection (nor model uncertainty).

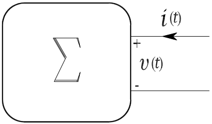
- A strict causality relation, motivated by the presence of sensors and actuators, is adopted. Consequences:
  - Overall system is “closed and isolated".
  - Difficult, if not impossible, to couple with other systems.
- Focus on the details of the system, neglecting the interactions. Rationalized via:
  - Time-scale separation arguments, and
  - “high impedance" considerations.

Prevailing Signal-processing Viewpoint of Control

- System model and controller are signal processors: $G_i : e_i \mapsto y_i$.



- Control specifications in terms of signals.
- PBC: View systems and controllers as energy processors



- Control achieved via "energy" exchange.
- Control objective to "shape it"

2. Passivity: The Key Articulating Concept

On the Role of Passivity

- Why is passivity important?
  - For physical systems it is a restatement of energy conservation.
  - Is a natural generalization (to NL dynamical systems) of phase-shift of LTI systems–sign preserving property.
- Term Passivity-based Control (PBC) introduced in

  R. Ortega and M. Spong, Adaptive Motion Control of Rigid Robots: A Tutorial, *Automatica*, Vol. 25, No. 6, 1989, pp. 877-888,

  to define a controller methodology whose aim is to render the closed-loop passive.
- The paper has been cited more than 1200 times and
- PBC has more than 9,500 hits in Google scholar.

Passivity-Based Control: An Energy-Processing Viewpoint

- View plant as energy-transformation multiport devices
- Physical systems satisfy (generalized) energy-conservation:

$$\text{Stored energy} = \text{Supplied energy} + \text{Dissipation}$$

- Control objective in PBC: preserve the energy-conservation property but with desired energy and dissipation functions

$$\text{Desired stored energy} = \text{New supplied energy} + \text{Desired dissipation}$$

In other words

$$\text{PBC} = \text{Energy Shaping} + \text{Damping Assignment}$$

- In PBC plant and controller are energy-transformation devices, whose energy is added up.
- For general (non-passive) systems achieve a passivation objective

Advantages of PBC

- Energy and dissipation are additive.
  - Applicable to NL systems.
  - Suitable to handle interconnections of open systems.
  - Model uncertainty, *e.g.*, friction, naturally captured.
- Shaping energy and dissipation there's a handle on performance, not just stability
- Respect, and effectively exploit, the structure of the system to
  - incorporate physical knowledge,
  - provide physical interpretations to the control action.
- Energy conservation is a universal property, hence PBC is applicable to multi-domain physical systems.
- Energy serves as a lingua franca to communicate with practitioners.
- There's an elegant geometric characterization of port-Hamiltonian systems (via Dirac structures).

Applications

- Mechanical systems: walking robots, bilateral teleoperators, pendular systems.
- Chemical processes: mass-balance systems, inventory control, reactors.
- Electrical systems: power systems, power converters.
- Electromechanical systems: motors, magnetic levitation systems, windmill generators.
- Transportation systems: underwater vehicles, surface vessels, (air)spacecrafts.
- Control over networks: formation control, synchronization, consensus problems.
- Hybrid systems: switched systems, hybrid passivity.
- ⋮

3. Mathematical Formulation of PBC

Class of Systems

Definition We say that an m-port system, with state $x \in \mathbb{R}^n$, and power port variables $(v, i) \in \mathbb{R}^m$, is cyclo-passive if

$$\underbrace{H[x(t)] - H[x(0)]}_{stored \quad energy} \leq \underbrace{\int_0^t i^\top(s) v(s) ds}_{supplied}$$

where $H : \mathbb{R}^n \to \mathbb{R}$ is the stored energy function. If $H(x) \geq 0$ then we say that the system is passive.

Corollary For passive systems we have

$$-\int_0^t v^\top(s) i(s) ds \leq H[x(0)] < \infty \quad \Rightarrow \text{ Bounded extracted energy}$$

Power Balance

$$\dot{H} = i^\top v + d,$$

where $d \geq 0$ is the dissipation.

Stabilization via Energy Shaping and Damping Injection

- The "free" system satisfies

$$H[x(t)] \leq H[x(0)] \qquad \Rightarrow$$

  - Trajectories tend to converge to points of minimum energy
  - If the minima are strict $H(x)$ is a Lyapunov function for them

- Energy shaping: To operate the system around some desired equilibrium point, say $x_\star$, PBC shapes the energy to assign a strict minimum at this point.

- Damping injection: Terminate the port with a resistor, *i.e.*,

$$v = -K_{di} i, \quad K_{di} = K_{di}^\top > 0$$

  we get

$$\dot{H} \leq -i^\top K_{di} i \leq 0.$$

  Hence, $x(t) \to x_\star$ if $[i(t) \equiv 0 \ \Rightarrow \ x(t) \to x_\star]$. That is, if i is a detectable signal.

Formulation of PBC (for Equilibrium Stabilization)

Objective Transform the power balance equation into

$$\dot{H}_d = v^\top y_d - d_d$$

- H_d is the desired total energy function, which has a minimum at $x_\star$,
- $d_d(t) \geq 0$ desired damping, and
- y_d is the new passive output.

Several ways to shape the energy [$\Leftrightarrow$ assign a Lyapunov function]:

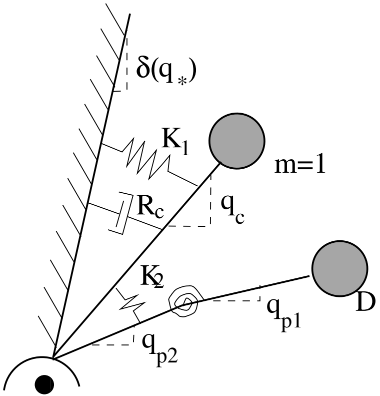
- Control by Interconnection.
- Interconnection and damping assignment.
- Standard PBC of Euler-Lagrange systems: $H(x) = \frac{1}{2}x^\top D(x)x$, $D > 0$, we assign

$$H_d(x, x_d) = \frac{1}{2}(x - x_d)^\top D(x)(x - x_d),$$

  with (part) of x_d the controller state.
- PID-PBC.

Application to Underactuated Mechanical Systems

Flexible Joint Robots



Application to Underactuated Mechanical Systems

- Plant energy:

$$H(q_p, p_p) = \frac{1}{2} p_p^\top D^{-1}(q_p) p_p + V(q_p)$$

- Controller energy:

$$H_c(q_c, p_c, q_{p2}) = \frac{1}{2}|p_c|^2 + \frac{1}{2}(q_c - q_{p2})^\top K_2 (q_c - q_{p2}) + \frac{1}{2}(q_c - \delta)^\top K_1 (q_c - \delta)$$

- Controller Rayleigh dissipation function:

$$\mathcal{F}(\dot{q}) = \frac{1}{2} \dot{q}_c^\top R_c \dot{q}_c.$$

- Rigid case solved in (Kelly'93), with flexibility in (Ailon/Ortega, SCL'93)

Notation

Notation

- Vectors and matrices. All vectors, column vectors, $b \in \mathbb{R}^n$, $b = \text{col}(b_1, \dots, b_n)$, $e_i \in \mathbb{R}^n, i = 1, \dots, n$-Euclidean basis. Matrices, $B \in \mathbb{R}^{n \times m}$, $B = \{B_{ij}\}$.
- Definition. Let $B \in \mathbb{R}^{n \times m}$, $m < n$ with rank $B = m$. The matrix $B^\perp \in \mathbb{R}^{(n-m) \times n}$ is a full rank left annihilator of B, if $B^\perp B = 0$ and rank $B^\perp = n - m$.
- Mappings. Functions, $h : \mathbb{R}^n \to \mathbb{R}$; vector fields, $f : \mathbb{R}^n \to \mathbb{R}^n$, $f(x) = \text{col}(f_1(x), \dots, f_n(x))$; mappings $G : \mathbb{R}^n \to \mathbb{R}^{n \times m}$, $G(x) = \{G_{ij}(x)\}$. All assumed "sufficiently" differentiable.
- Given $x^\star \in \mathbb{R}^n$ define $G^\star := G(x^\star)$.
- Differential operators. For functions of scalar argument, $(\cdot)'$ denotes its derivative. For $h : \mathbb{R}^n \to \mathbb{R}$:

$$\nabla h := \left(\frac{\partial h}{\partial x}\right)^\top : \mathbb{R}^n \to \mathbb{R}^n, \ \nabla^2 h := \frac{\partial^2 h}{\partial x^2} : \mathbb{R}^n \to \mathbb{R}^{n \times n}.$$

References on PBC for Mechanical Systems

Books

- T. Hatanaka, N. Chopra, M. Fujita, and M. W. Spong, *Passivity–Based Control and Estimation in Networked Robotics*, Springer International, Cham, Switzerland, 2015.
- R. Ortega, A. Loria, P. Nicklasson, and H. Sira-Ramirez, *Passivity-based control of Euler-Lagrange systems: mechanical, electrical, and electromechanical applications*, Springer-Verlag, London, 1998.
- R. Ortega, A. Donaire et J. Romero, Passivity–based control of mechanical systems, in *Feedback Stabilization of Controlled Dynamical Systems*, eds N. Petit, Lecture Notes in Control and Information Sciences vol. 473, Springer Berlin/Heidelberg, pp. 167-199, 2017.

“Classical" Papers

- J. A. Acosta, R. Ortega, A. Astolfi, and A. M. Mahindrakar, Interconnection and damping assignment passivity–based control of mechanical systems with underactuation degree one, *IEEE Transactions on Automatic Control*, 50(12):1936–1955, 2005.
- A. Ailon and R. Ortega, An observer–based controller for robot manipulators with flexible joints, *Systems & Control Letters*, 21(4):329–335, 1993.
- G. Blankenstein, R. Ortega, and A. J. van der Schaft, The matching conditions of controlled Lagrangians and interconnection assigment passivity based control, *International Journal of Control*, 75(9):645–665, 2002.
- A. D. Mahindrakar, A. Astolfi, R. Ortega, and G. Viola, Further constructive results on IDA–PBC of mechanical systems: The Acrobot example, *International Journal of Robust and Nonlinear Control*, 16:671–685, 2006.
- R. Ortega and M. W. Spong, Adaptive motion control of rigid robots: a tutorial, *Automatica*, 25(6):877–888, 1989.
- R. Ortega, M. W. Spong, F. Gomez, and G. Blankenstein, Stabilization of underactuated mechanical systems via interconnection and damping assignment, *IEEE Transactions on Automatic Control*, 47(8):1218–1233, 2002.
- M. Takegaki and S. Arimoto, A new feedback for dynamic control of manipulators, *Transactions of the ASME: Journal of Dynamic Systems, Measurement and Control*, 12:119–125, 1981

cont'd

Recent Results

- N. Crasta, R. Ortega, and H. Pillai, On the matching equations of energy shaping controllers for mechanical systems, *International Journal of Control*, 88(9):1757–1765, 2015.
- A. Donaire, R. Mehra, R. Ortega, S. Satpute, J. G. Romero, F. Kazi, and N. M. Singh, Shaping the energy of mechanical systems without solving partial differential equations, *IEEE Transactions on Automatic Control*, 61(4): 1051–1056, 2016.
- A. Donaire, R. Ortega, and J. G. Romero, Simultaneous interconnection and damping assignment passivity–based control of mechanical systems using dissipative forces, *Systems & Control Letters*, Vol. 94, pp. 118-126, 2016.
- A. Donaire, J. G. Romero, R. Ortega, B. Siciliano, and M. Crespo, Robust IDA–PBC for underactuated mechanical systems subject to matched disturbances, *International Journal of Robust and Nonlinear Control*, Vol. 27, No. 6, pp. 1000-1016, 2017.
- P. Gandhi, P. Borja and R. Ortega, Energy shaping control of an inverted flexible pendulum fixed to a cart, *Control Engg. Practice*, Vol. 56, pp. 27-36, 2016.
- J. G. Romero, R. Ortega and A. Donaire, Robust energy shaping control of mechanical systems without solving PDEs and extension to constant speed tracking, *IEEE Transactions Automatic Control*, Vol. 61, No. 11, pp. 3551-3556, 2016.
- J. G. Romero and R. Ortega, Two globally convergent adaptive speed observers for mechanical systems, *Automatica*, 60:7-11, 2015.
- J. G. Romero, A. Donaire, and R. Ortega, Robust energy shaping control of mechanical systems, *Systems & Control Letters*, 62(9):770–780, 2013.
- J. G. Romero, R. Ortega, and I. Sarras, A globally exponentially stable tracking controller for mechanical systems using position feedback, *IEEE Transactions on Automatic Control*, 60(3):818-823, 2015.
- J. G. Romero, A. Donaire and R. Ortega, Global stabilisation of underactuated mechanical systems via PID passivity-based control, *Automatica*, (to be published).
- A. Venkatraman, R. Ortega, I. Sarras, and A. van der Schaft, Speed observation and position feedback stabilization of partially linearizable mechanical systems, *IEEE Transactions on Automatic Control*, 55(5): 1059-1074, 2010.