Why Energy in Robotics?

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Happy Birthday Alessandro!!!
Let’s Start with some memories..
Vi faccio un ..... così!

“O sole mio…” (mi abbaglia)
ICRA 2011, Shanghai, (11th of May)
IROS 2012, Vilamoura, (8th of October)
I am so young! Only 55 years old!!

IROS 2012, Vilamoura, (11th of October)
ICRA 2015, Seattle, (27th of May)
(The Music Lovers)
Content

- About Paradigm Shifts
- Why EXPLICITLY using energy methods in robotics
- Example of a “difficult problem” made simple
- Conclusions & Future Work
In this article we consider the objective of efficient transfer of electric energy between subsystems, where each subsystem can generate, store, or consume energy. An application example is a multidomain system consisting of a fuel-cell-based generating unit, batteries, supercapacitors, and electric motors or generators; this topology is used in some electric cars. Depending on the operation regime, energy must be transferred between the various units, which we refer to as multiports, according to some energy-management policy. To ensure energy exchange, the interconnection of the storage and load devices is performed by using power converters. These subsystems are electronically switched circuits capable of adapting the port voltage or current magnitudes to a desired value.

To achieve energy transfer between multiports, it is common practice to assume that the system operates in steady state and then translates the power demand (flow sense and magnitude) of the multiports into current or voltage references. These references are then tracked with control loops, usually proportional plus integral (PI). Since the various multiports have different time responses, it is often necessary to discriminate between quickly and slowly changing power-demand profiles. For instance, due to physical constraints, it is not desirable to demand quickly changing power profiles to a fuel-cell unit. Hence, the peak demands of the load are usually supplied by a bank of supercapacitors, whose time response is fast. To achieve this objective, a steady-state viewpoint is again adopted, and the current or voltage references to the multiports are passed through lowpass or highpass filters. For further details, see "Criteria for Current-Reference Selection."

The steady-state approach currently adopted in practice can only approximately achieve the desired objectives of energy transfer and slow-versus-fast discrimination of the power demand. In particular, during the transients or when fast dynamic response is required, the delivery of demanded power in response to current or voltage references and the time response action of the filters might be far from satisfactory.

In this article we present an energy router that dynamically controls energy flow. The router operational principle...
Energy (and Geometrical) Aware Robotics

Robots and Interaction follow the laws of physics!
Energy or no Energy, that is the question

- No relation with energy
  - No way to work in all situations during interaction
  - No robustness
  - Environment cannot be “properly modeled”!
  - Unespected behaviour
  - ...

- Passivity or better: Energy Awareness
  - Track and Control Energy flows
  - Never problems with stability
  - Robust
  - Can Couple Digital-Continuos World
  - Handle Time delays
  - .....
Geometry or no Geometry, that is the question

- **No Geometry**
  - Complicated equations
  - Solutions dependent on coordinates
  - Non physical nonsense: eigenvalues of Inertias, random ortogonality, projections, non invariant indeces,…
  - Singularity
  - Unexpected instabilities

- **Geometry**
  - Simple description
  - Coordinate Invariant
  - Physical
  - No singularity
  - Directly see if something is wrong: inverses, projections, error measurement

...
Modelling

Port Based Thinking
What is it and why is this useful?
Any physical system has this structure:

- Power Continuous (C)
- Energy Storage
- Entropy (R)
- Energy "dissipation"

Interconnections:
- Interconnection 1
- Interconnection 2
- Interconnection n

Possible Energy direction can be time varying.
Conjecture

To ensure stability *during any interaction* control needs to be implemented by Interconnection either physically or by control
Control by Design or Control by Interconnection

Diagram:
- Controller
- Power Continuous
- Environment/Humans
- RS
- Entropy

C

RS
Control by Design or Control by Interconnection

Modify the design:
• Adding elements
• Change how they are connected
Control by Design or Control by Interconnection

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Examples

• Change “Resonance” by parallel springs

• Generate Forces needed elastically to avoid dissipation and irreversibility in drive chains


Control by Design or Control by Interconnection

Modify the design:
• Adding elements
• Change how they are connected

Diagram:
- Power Continuous
- Environment/Humans
- Entropy
- RS
Control by Design or Control by Interconnection

Modify the design:
• Adding elements
• Change how they are connected

Implement "Dampers with springs": Instead of implementing damping forces with dissipating elements, try to do it with elastic elements.
Control by Design or Control by Interconnection

Modify the design:
• Adding elements
• Change how they are connected

Implement "Dampers with springs": *
Instead of implementing damping forces with dissipating elements, try to do it with elastic elements
Control by Design or Control by Interconnection

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Implement "Dampers with springs":
Instead of implementing damping forces with dissipating elements, try to do it with elastic elements
Theorem: Passivity Control Robot (PCR)

Given a non-passive system \( \Sigma_{cr} \) (controlled robot) with input output pair \((u, y)\) (representing the interaction with the environment), there exists always a passive system \( \Sigma_e \) (environment) which connected to the \( \Sigma_{cr} \) will give rise to an unstable behaviour of the interconnection of \( \Sigma_e \) and \( \Sigma_{cr} \).
Control by Design or Control by Interconnection

Modify the design:
- Adding elements
- Change how they are connected

Implement "Dampers with springs": Instead of implementing damping forces with dissipating elements, try to do it with elastic elements.
Control by Design or Control by Interconnection

Variable Compliance is the most basic and essential dynamic shaping paradigm

Continuous Time World: Real Energy
Control by Design or Control by Interconnection

- Variable Compliance is the most basic and essential dynamic shaping paradigm.

**Discrete Time World:** Virtual Energy
- All Needed Damping can be regenerative.

**Continuous Time World:** Real Energy
- Low Dissipation Reversible Power
- All Needed Damping can be regenerative.

How to keep consistency between Virtual and Real Energy?
Passive Sampling

\[ e_D(t) = \tilde{e}_D(k) \quad t \in [kT, (k + 1)T] \]

\[ \Delta E^{in}_C = \int_{kT}^{(k+1)T} \tilde{e}_D^T f_D(s) ds = \tilde{e}_D(k) \int_{kT}^{(k+1)T} f_D(s) ds \]

\[ = \tilde{e}_D(k)(q((k + 1)T) - q(kT)) \]

S. Stramigioli, C. Secchi, A. J. van der Schaft, and C. Fantuzzi, “Sampled Data Systems Passivity and Discrete Port-Hamiltonian Systems,” IEEE transactions on robotics,
This actually works!

Standard PD  IPC PD

30 Hz sample rate
Implementation

Put Intelligence as much as possible in the mechanics: embedded intelligence
Control by Design or Control by Interconnection

How to keep consistency between Virtual and Real Energy?

Variable Compliance is the most basic and essential dynamic scaping paradigm.

Low Dissipation Reversible Power Flows

All Needed Damping can be regenerative

Continuous Time World: Real Energy

Discrete Time World: Virtual Energy

Environment/Humans
Irreversible Impacts absorption
Then the brush is activated.
Patented

- Stator
- Rotor
- Output
- Hypocycloid gearing
- Leaf springs
- Leaf spring clamps
Example: A difficult problems made simple

Interactive, Distributed Architecture with time varying delays
Environment

Mechanism

Act-1
FW

Act-2
FW

Act-n
FW

sensing

Variable, Different Time delays: computation, communication..
Conclusions
Conclusions

• To analyse or develop systems for the sake of optimising energy consumption, **proper tools/language** as needed or at least useful

• To ensure proper behaviour during interaction, the digital control needs to also be **energy aware**

• The coupling of the continuous and discrete part of the system can be made energy consistent: **energy consistent sample and hold**

• Port-Based / Energy Aware Robotics can help in innovative design by **giving insight in the energy flows**.
Future Work
Speed up to 80 Km/h in 5 bfr wind
Reversed Von Kármán sheet generation

Strouhal number \((0.2 < St < 0.4)\)
Variable boundaries, port-based Navier-Stokes
Dear Alessandro, congratulations again and thanks!

The sky is **not** the limit,

..but just the first layer

THANK YOU FOR YOUR ATTENTION