Energy-Oriented Design, Control and Optimization of Robotic Systems

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Modeling

Most of our research has been based on torque-driven robotic manipulators:

$$D^{\circ}(q)\ddot{q} + C(q,\dot{q})\dot{q} + \mathcal{R}^{\circ}(q,\dot{q}) + g(q) + \mathcal{T} = \tau \tag{1}$$

The above equation starts with joint torque τ, which together with $\dot{q}$ are the power variables at the interface with the drive system. The superscripts indicate that the matrices do not account for drive characteristics. The drive is assumed to have the characteristics pointed out in the Introduction document. Many drives can be captured by the same bond graph, regardless of domain (electromechanical, hydraulic, etc.). This means that the structure of the model is the same, using analogies across domains. Generalities are discussed in [3]. We will focus on electromechanical drives.

The goal is to model the drive and combine it with Eq. 1 to form an augmented model and reveal the control input. We divide drives into *semiactive*, described in the Introduction document, and *active*. The latter captures the possibility of direct torque command: the torque applied to active joints is proportional to that joint's control input (some invertible nonlinear function also works, $\tau_i = f_i(u_i)$, $u_i = f_i^{-1}(\tau_i)$.)

Semiactive drives contain a mechanical transmission, a power conversion element (control access point) and an energy storage element. We've used *supercapacitors*, also known as *ultracapacitors* for most of the work, modeling them first with simple capacitive laws $i = C\dot{V}$. Then we realized that *no such models are needed* when using our approaches, since we use real-time voltage feedback, which substitutes for models. This allowed us to consider *general storage elements*, provided they have a voltage-current port and their stored energy is a 1-1 function of voltage.

Using standard modeling or bond graph approaches, we obtain the interface torque

$$\tau_j = -m_j n_j^2 \ddot{q}_j - (b_j n_j^2 + \frac{a_j^2}{R_j})\dot{q}_j + \frac{a_j r_j}{R_j} V_s \tag{2}$$

where $a_j = \alpha_j n_j$ and V_s is the storage element voltage, and the other parameters reflect the gear ratio, inertial characteristics, damping ad resistance of the drive. Details of this derivation appear in [1].

Sign convention: If $\tau_j \dot{q}_j > 0$, we are in the regeneration mode, implying that power flows from the manipulator to the drive, towards the storage element.

Interconnection Effects

Each drive is mechanically connected to a robot joint. If each drive has its own storage element, we call this the *distributed configuration*. If there is one storage element common to all drives, we call this the *parallel, or star configuration*.

The star configuration is interesting, because it allows power transfer from a joint experiencing a power surplus to one experiencing a power demand, balancing the load and improving the system's energy efficiency. This transfer is through regeneration, using the common storage element as a buffer, or big communal pot where energy may be added or removed.

There are some simple relationships between the star and distributed configuration which allowed us to study only one case. The details of this equivalence are fully developed in [2] and [1].

Augmented Model

Assume that the star configuration is used. Then V_s is the same for all joints. When the interface torque is combined with the manipulator, an augmented model is obtained:

$$D(q)\ddot{q} + C(q,\dot{q})\dot{q} + \mathcal{R}(q,\dot{q}) + g + \mathcal{T} = u \tag{3}$$

where D and $\mathcal{R}$ are

$$\begin{array}{ll} D_{ij} = D^{\circ}_{ij} & i \neq j \\ \mathcal{R}_j = \mathcal{R}^{\circ}_j & j \notin \{1,\dots,e\} \\ D_{jj} = D^{\circ}_{jj} + m_j n_j^2 & j \in \{1,\dots,e\} \\ \mathcal{R}_j = \mathcal{R}^{\circ}_j + (b_j n_j^2 + \frac{a_j^2}{R_j}) & j \in \{1,\dots,e\} \end{array} \tag{4}$$

and

$$u = \begin{cases} u_j & \text{Joint } j \text{ is fully-active} \\ \dfrac{a_j r_j}{R_j} V_s & \text{Joint } j \text{ is semi-active} \end{cases} \tag{5}$$

Fully-active joints are directly controlled with u_j, which is typically an analog input voltage to a torque-mode servo amplifier. For the semi-active joints, only r_j is available as a control variable.

The control input is the ratio of motor and storage element voltages. The above assumes an ideal power converter acting as a transformer. Ideal means linear, 100% efficient and without dynamics. Non-ideality could be accounted for by adding appropriate effects on each side of an ideal transformer, which remains at the core of the electromechanical power conversion.

There are regenerative drives that closely correspond to what we modeled. They are also referred to as 4-quadrant converters. We used the inexpensive SyRen units, manufactured by Dimension Engineering, in Hudson, Ohio. Their control input can be scaled to correspond exactly to our r_j.

Note: In [3] we considered variable gear ratios $n_j(q)$. Even with that, the augmented mass and Coriolis matrices satisfy the fundamental properties of symmetry and positive-definiteness for D and skew-symmetry of $\dot{D} - 2C$. These properties are very useful for robust and adaptive controller design in robotics. The linear parameterization property, however, may be no longer accessible for general forms of $n_j(q)$, but it remains so for constant n_j.

Why supercapacitors? The main reason is their ability to *receive* as well as deliver large currents. Batteries are severely limited in their charging currents. Supercapacitors, even small lab units, can be charged at hundreds of amps without problems. This is key for maximum recovery of regenerative energy. Also, they are lightweight and very durable. However, they do not store nearly as much charge as batteries.

There's a domain of application where supercapacitors a very good fit, and this is mobile robots and biomedical robots.

References

[1] P. Khalaf. *Design, Control, and Optimization of Robots with Advanced Energy Regenerative Drive Systems.* PhD thesis, Cleveland State University, 2019.

[2] Poya Khalaf and Hanz Richter. On global, closed-form solutions to parametric optimization problems for robots with energy regeneration. *Journal of Dynamic Systems, Measurement, and Control*, 140(3):031003, 2018.

[3] Hanz Richter. A framework for control of robots with energy regeneration. *Journal of Dynamic Systems, Measurement, and Control*, 137(9):091004, 2015.