Eco Motion Planning for mechatronic systems

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Abstract. Saving energy while retaining productivity is one of the most desired features in modern production industry, which is currently responsible for a notable amount of the worldwide energy need. Cutting down the costs of an energivorous plant does not just provide economic savings, but it also reduces the carbon footprint of commercial products. In this chapter, the wise use of energy in mechatronic systems is discussed, by focusing on Eco Motion Planning (EMP). The basic idea is that a optimized motion planning, in term of selection of the motion time, of the motion profile, of the spatial trajectory and the of motion scheduling, can remarkably reduce energy absorption without affecting the throughput of the mechatronic system. The chapter briefly reviews the most relevant methods that have been proposed in the literature, ranging from simple machines with constant inertia to industrial robots, and provides the most relevant equations and models of the energy consumption that can be used in EMP. A numerical test case is then analyzed to outline a method for designing an energy optimal motion profile and an optimal scheduling in a robotic cell made by a system with constant inertia, and a multi-axis robot governed by a nonlinear dynamic model. Despite its conceptual simplicity, the proposed method ensures remarkable energy improvements while retaining productivity and without requiring any physical alteration of the plant and clearly proves the benefit of EMP.

Keywords: Energy saving, sustainability, motion planning, robotic cells, mechatronic systems

1 Introduction

Improving energy efficiency of mechatronic systems, while preserving high throughput, is one of the key goals of eco-mechatronics [1] since current trends reveal that global energy demand is expected to grow at a constant rate over the next decades [2]. The relevance of this topic is also testified by the directions set by the European Union policy [3] whose goal is reducing the primary energy consumption of 30% by 2030. A significant amount of the worldwide energy absorption is related to manufacturing processes, where, in turn, a relevant contribution is due

to the energy required by automatic machines and robots adopted to perform simple activities with a small added value, such as moving tools or conveying products. A cost-free approach to improve energy efficiency of mechatronic systems is therefore the optimization of these phases by means of the optimization of the planned motion: a wide literature, that will be reviewed in the following, has shown that energy savings up to 30% can be achieved by a wise motion planning focused on the energy absorption, compared to traditional approaches that usually discard this issue. Several techniques have been developed in the literature, thus providing effective solutions for a wide range of machines and robots used in modern industries. Optimization basically involves the selection of the spatial path and of the motion law (often including the duration of motion). If at least two machines are taken into account, also the scheduling of the operation can boost energy efficiency [4]. Indeed, besides optimizing the energy consumption of each axis, a wise scheduling of motion can optimize the energy exchange between accelerating and decelerating axes when regenerative drives are used. The enhancement of the planned motion represents in many cases the most feasible solution for energy saving since it can be applied both when commissioning a new system as well as when retrofitting an existing one, with no physical modifications of the electromechanical devices.

The discussion provided in this chapter covers some general issues and their solutions, focusing on methods that are suitable to both researchers and industry practitioners. The first goal of the chapter is to provide a general overview of the methodologies used in modeling and analysis of the energy consumption of mechatronic systems, together with their use for reducing the energy absorption. These two issues are the pillars on which the idea of Eco Motion Planning (EMP) is rooted on; optimization of the spatial path, of the timing law and of the scheduling are the tools exploited by EMP for improving energy efficiency. Then, the chapter provides and discusses some models of energy absorption, and their use in EMP is proposed through two meaningful examples. The first example consists of the common case of a constant inertia system, as those often adopted in industry, where EMP can be solved through some analytical equations. Then, by considering a multi-axis system with nonlinear dynamic behaviour, a different solution technique is proposed by exploiting numerical methods for the solution of the resulting multivariate optimization problem.

2 Literature review

Motion design, in its most general definition, is a branch of mechatronics and robotics that deals with the definition of the reference profiles to be executed by an automatic machine. This general problem applies to basic systems as well to very complex ones, such as robotic cells with several robots and some auxiliary axes. This variety of applications has produced a literature on motion planning that counts for, literally, hundreds of related works. Reviewing all of them is outside the scope of this work: here just a brief overview of the most common applications of EMP is provided. For a general overview of trajectory planning

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the reader should refer to the classic titles, such as [5,6,7,8]. A detailed list of papers on the problem of boosting energy efficiency by means of motion design is provided also in [9], that quotes also other methods not strictly related to motion design, which are therefore outside the scope of this chapter.

The most investigated problem in EMP is the rest-to-rest motion of a single degree-of-freedom (DOF) system with constant inertia. A meaningful example of a commonly used method can be found in [10], which provides an analytic treatment of the energy consumption and of the optimal motion time of a single servo-driven axis with constant inertia when executing standard motion primitives. This work and several related ones share a similar outline: the energy consumption is found by the time integration of the algebraic equations representing the electric power profile, computed through the system electromechanical model that includes the inverse dynamic model of the mechanical part and a simplified model of the motor. The energy consumption therefore takes the form of a function of some parameters, allowing for a simple optimization either through analytical equations, as proposed in [10] and in the more recent paper [11], or through some basic numeric methods based on computing the stationary points of simple cost functions, as proposed in other works, such as [12], [13], [14]. Among the analytical solutions of the energy optimal motion planning, the one proposed in [10] results in very simple equations, since the features of the different motion primitives are summarized through few coefficients that allow for a straightforward calculation and comparison. Simple analytical formulations of the energy consumption can be formulated for Cartesian robot as well, due to the decoupling between the axis [15].

Some works have followed different approaches: for example, [16,17,18] solve energy-optimal point-to-point motion within the framework of variational calculus. Hence, the energy minimization problem is approached as an indirect optimization on or an optimal control problem, which usually require elaborate solution methods [19]. Within a variational problem formulation, the motion profile is generally not constrained to a specific parametrized description of the motion profile (for example, by means of a polynomial function), but it is free to assume any form within the feasible bounds: hence, among the infinite possibilities, a variational problem formulation computes the optimal motion law as the optimal sequence of positions (and consequently speeds and accelerations) that minimizes a given cost function. Variational solutions are virtyally effective in finding the optimal solution; however they might fail to converge and handling nonlinearities and hard constraints is usually very cumbersome [20]. Additionally, they are hardly appealing for industry practitioners since require specific solvers.

If mechatronic systems with variable inertia are considered, the use of closed form solutions is usually impracticable and numerical computation routines should be adopted: the complexity of the nonlinear equations of motions of even a single-DOF system is generally too high to be handled by simple calculations. For example, in [21,22] numerical methods are adopted to solve the algebraic equations and then to minimize the energy consumption of a toggle mechanism.

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Difficulties are exacerbated in the case of multi-DOF systems, such as robots. A general overview of the problem is provided in [23], which also sports a well supported analysis of the various sources of dissipation in industrial robots. A paper to be mentioned is [24], which proposes a commonly used and technically sound approach for EMP in robot: the optimization of a robot task as the result of an optimization procedure. The task is first designed by choosing a set of via-points that ensure a collision-free operation, then an interpolation procedure is used to define the energy-optimal motion, using a meta-heuristic optimization tool. The work [25] deals with the planning of a task that involves at least three via-points, which are to be connected by straight lines and arcs, i.e. by exploiting the most common motion primitives used in industrial robots. The optimization is performed by searching for alternative paths that pass close to the prescribed via-points without affecting the cycle time. A similar approach is proposed in [26] as well, where different motion primitive, such as B-splines, are used to interpolate via-points. In [27] and [28], functionally redundant robots are discussed, and the motion of the redundant degrees of freedom is optimally designed to reduce the energy required to perform the task, by exactly passing through some prescribed via-points. Numerical optimization routines are adopted due to the nonlinear dynamic model of the robot.

To handle the complexity of robotic systems, some authors have suggested the use of the so-called "CAD-based simulators", such as in [29,30], to exploit the capabilities of the multibody dynamics simulators embedded in most advanced CAD packages. that allow running simulations of the dynamics of the device under development without having to explicitly define a dynamic model. These approaches are therefore based on the solution of the differential equations governing the studied systems, by means of repeated simulations to optimize the motion design. These approaches are often denoted as "direct" approaches [10], since optimization often relies on trial-and-error procedures or enumeration and comparison of different solutions. CAD-based simulations are the key elements of the optimization procedures developed in other works as well, among which [31,32] are worth of mention, where simulations are exploited to predict and hence optimize energy consumption.

Model-free approaches have been proposed as well, to overcome the difficulties in developing reliable models of the energy consumption and to correctly identify their key parameters. One example of such an idea is found in [33], in which some ways to estimate the energy consumption of a robot without having to explicitly develop a dynamic model of the robot, for example by using identification methods applied to simulated data, are suggested. A different techniques is suggested in [34], where the data recorded by executing some trajectories with an industrial robot are used to develop a black box model to be used as the staring point for trajectory optimization. Another model-free approach has been developed in [35,36]: the method relies on the use of the native robot software and on the optimization of alternative cost functions, which can be based, for example, on pseudo-power (i.e. speed to acceleration product), jerk, or weighted joint accelerations. The authors mention a reduction up to 30% of the overall

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energy consumption for a given task without altering the execution time or the path.

Finally, a different approach to improve the energetic efficiency of a robot without the explicit use of a dynamic model is the one based on the use of some performance idexes. One example is found in [37], that analyses the relationship between the motion profile and the location of the task to be executed within the workspace, by taking into consideration a 4-DOF parallel robot. The outcome of this work is the development of energy maps that can guide the practitioners to position, whenever possible, the task in an energy-optimal location. In a related work [38] the approach is generalized by defining two energy and trajectory-related indexes that can be helpful not only during the robot programming phase, but also in a previous stage, for example during the design of the cell or of the robot. In this case the definition of an energetically sound trajectory is achieved by the minimization of a performance index based in inertia ellipsoids, and thus the numerical integration of the inverse dynamics electro-mechanical model of the robot is not needed.

This brief overview of motion-related energy optimization methods has highlighted a rather wide array of solutions and applications: the next section will guide the reader through an example of motion optimization that follows one among the most popular approaches, exploiting nonlinear optimization as the tool to define an energy-optimal motion profile for a robotic cell.

3 A paradigmatic test case: a robotic cell

The aim of this section is to discuss two techniques for EMP, that recall the common approaches adopted in the quoted literature, to analyze and optimize the energy efficiency of a robotic cell composed by a SCARA robot and a linear unit. The robotic cell involves two mechatronic systems with different features that are widely adopted in manufacturing plants: the linear unit is a constant inertia single-DOF mechanism, while the robot is a multi-axis system with variable inertia Discussing this paradigmatic example allows explaining two different approaches to EMP, by clarifying some issues discussed in the Introduction.

The task taken into consideration is split into two main phases to highlight different features: in the first phase the product is conveyed by the linear unit, and the end-effector of the robot is moved from the pallet to the location where the product can be picked up. In the second phase, the product is displaced by the robot, while the linear unit returns to the starting position with no load. The two devices are mechanically decoupled and therefore they can be modeled and analyzed independently from the other. Additionally, it is assumed that no energy regeneration between them is allowed: the energy absorption models are therefore decoupled as well. The system is represented in figure 1.

It is assumed that the whole operation has to be optimized for maximum energy efficiency while retaining a fixed total execution time. As an example, it has been assumed that 10 pieces are to be processed in one minute, leading to a cycle time equal to 6 s. The available degrees of freedom are the relative

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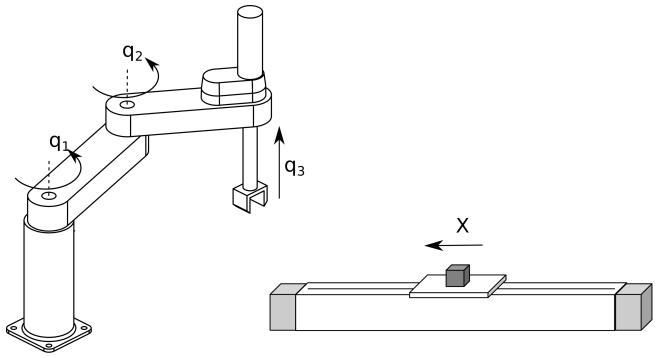

Fig. 1. Layout of the robotic cell: SCARA robot and linear unit

duration of the two phases, and some parameters representing the motion law in time of the linear unit and of the robot during each phase. Some resting phases, if beneficial to reduce the energy consumption, can be included in scheduling the operations.

4 Energy optimization

In this section the energy optimization of the system is developed by exploiting the electro-mechanical models of the two systems. The inverse dynamics, algebraic model representing the energy consumption of the linear unit can be integrated both numerically and analytically, while the robot dynamics should be integrated numerically due to the presence of nonlinearities.

4.1 Linear unit

The linear unit is composed by a belt-driven carriage, supported and guided by ball rails, and its actuation is provided by a brushless motor coupled to the pulley through a gearbox. The main parameters of the linear unit are provided in Table 1, which are extracted from the manufacturer's datasheet available in [39].

The dynamics of the linear unit can be described by the following equation:

$$T_m(t) = J_{LU}\ddot{\vartheta}_m(t) + k_{v,LU}\dot{\vartheta}_m(t) + T_{eq} \tag{1}$$

in which J_{LU} accounts for the reflected moment of inertia of the motor, of the gearbox, of the pulleys and of the mass of the carriage that conveys the product to be displaced. The equivalent static friction torque T_{eq} accounts for the contributions of the motor, of the gearbox and of the linear unit as well. Equation (1) can be used for the evaluation of the instantaneous torque required to track the desired speed and acceleration profiles. Hence, the torque profile $T_m(t)$ is known once the reference motion of the linear unit is defined.

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Table 1. Linear unit: relevant modeling parameters

Parameter	**Value**
Pulley radius R_p	$0.02626\ m$
Carriage weight m_c	$7\ kg$
Gear ratio i	5
Gearbox inertia J_r	$27 \times 10^{-6}\ kgm^2$
Equivalent inertia J_{eq}	$3.8784 \times 10^{-4}\ kgm^2$
Equivalent static friction torque T_{eq}	$0.434\ Nm$
Motor moment of inertia $J_{m,LU}$	$1.45 \times 10^{-4}\ kgm^2$
Motor viscous friction coefficient $k_{v,LU}$	$1.24 \times 10^{-4}\ Nms/rad$
Motor winding resistance R_{LU}	$2.51\ \Omega$
Motor torque constant $k_{t,LU}$	$0.74\ Nm/A$
Motor back-emf constant $K_{b,LU}$	$0.45\ Nms/rad$
Maximum speed v_{max}	$3\ m/s$
Maximum acceleration a_{max}	$50\ m/s^2$

The electric power consumption associated with a point-to-point task can be evaluated by modeling the voltage drop across the motor. According to the common approach adopted that the papers quoted in the introduction, the electromechanical model of the motor is defined by means of its DC-motor equivalent, i.e. by using the well-established Park's direct-quadrature-zero transformation [40]:

$$V(t) = RI(t) + k_b\dot{\vartheta}_m(t) + L\frac{dI(t)}{dt} \tag{2}$$

where the current absorbed by the motor is proportional to the exerted torque T_m:

$$I(t) = \frac{T_m(t)}{k_t} \tag{3}$$

k_t is the motor torque constant, R is its equivalent winding resistance, k_b is the back-emf constant, L is the motor winding inductance; all these parameters are usually listed in the motor datasheet. The electric power absorption of the motor that drives the linear unit is defined by the voltage-to-current product:

$$W = I(t)V(t) \tag{4}$$

and the energy consumed over the time frame $[0, \tau]$ is the integral of W, as in:

$$E_{LU} = \int_0^\tau W(t)dt \tag{5}$$

It should be pointed out that only the positive values of $W(t)$ are to be integrated in eq. (5) in the proposed example as it is assumed that the motor drive is

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not regenerative. This model suffices to properly estimate the energy associated with one work cycle, as proved by the literature (see e.g. [41,21]). As discussed in the introduction, EMP relies on the analytic computation of the energy, once the motion primitive is chosen or properly written as a function of some meaningful parameters (see e.g. [10]). In this work, as an example of a widely adopted motion profile, the so called "S-shaped" motion profile is assumed. This motion law is often used as a smoother alternative to the basic trapezoidal speed profile [7] since it provides continuity up to to the second derivative. It is conveniently described by splitting it into three phases (acceleration, constant speed, deceleration), leading to the following speed profile:

$$\begin{aligned} \dot{\vartheta}_m(t) &= \frac{v_{max}}{2}\left(1-\cos(\omega_1 t)\right) && t \in [0, \tau_a) \\ \dot{\vartheta}_m(t) &= v_{max} && t \in [\tau_a, \tau_f^{LU} - \tau_a) \\ \dot{\vartheta}_m(t) &= \frac{v_{max}}{2}\left(1+\cos(\omega_1 t)\right) && t \in [\tau_f^{LU} - \tau_a, \tau_f^{LU}] \end{aligned} \tag{6}$$

This motion profile is usually parametrized, in its symmetric form, by the total motion duration τ_f^{LU}, the acceleration (and deceleration) phase duration, τ_a, and by the overall displacement, h. The maximum speed is computed to ensure the proper displacement h, according to the simple relation:

$$v_{max} = \frac{h}{\tau_f^{LU} - \tau_a} \tag{7}$$

while continuity of acceleration is enforced by:

$$\omega_1 = \frac{\pi}{\tau_a} \tag{8}$$

This motion profile can also be conveniently formulated through the dimensionless ratio $\lambda{=}\tau_a/\tau_f^{LU}$, that is usually assumed as a tuning parameter to trade off between the conflicting requirements of reducing speed and acceleration (and hence torque) [7]. In this work, such a parameter is adopted to optimize the energy consumption, while complying with the specifications of the cycle of the robotic cell. The absorbed energy can be conveniently written as a function of λ and analytic integration of the algebraic equations can be performed, leading to a solution to the following optimization problem that represents EMP for the linear unit, for each of the two phases of the working cycle:

$$\begin{gathered} \min_{[\lambda]} E_{LU}(\lambda, \tau_f^{LU}) \\ \text{with: } \tau_f^{LU} \text{ fixed;} \\ \text{subject to: } \lambda_{min} \leq \lambda \leq \lambda_{max} \end{gathered} \tag{9}$$

The minimum and maximum values of λ are set to ensure the speed (v_{lim}) and acceleration (a_{lim}) limits:

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$$\lambda_{min} = \frac{\tau_f^{LU} a_{lim} - \sqrt{a_{lim}\left(2\pi h - a_{lim}\tau_f^{LU\,2}\right)}}{2\tau_f^{LU} a_{lim}} \tag{10}$$

$$\lambda_{max} = \min\left\{1 - \frac{h}{\tau_f^{LU} v_{lim}}, 0.5\right\} \tag{11}$$

Other limits could be easily included, such as those stated in [10]. Equation (9) sets a constrained nonlinear optimization problem, which is of fast and straightforward solution using standard numerical optimization routines.

The results of the solution of the optimization problem in eq.(9) for values of τ_f^{LU} up to 6 s (that is the overall cycle time), are plotted in figure 2. Each point of the graph refers to an optimal solution. Figure 2 shows, in the upper plot, the minimum energy required by the linear unit to perform the first phase of the motion to convey the product towards the robot. The total energy is plotted vs the total motion duration: each sample of the energy is evaluated by optimizing the energy consumption for a given value of τ_f^{LU}, and then for each τ_f^{LU} the ratio λ is optimized. The optimal values of λ are reported in the bottom plot of the same figure. τ_f^{LU} is lower limited by the constraints imposed by the maximum allowed speed and torque (and hence acceleration) due to the characteristic curve of the motor.

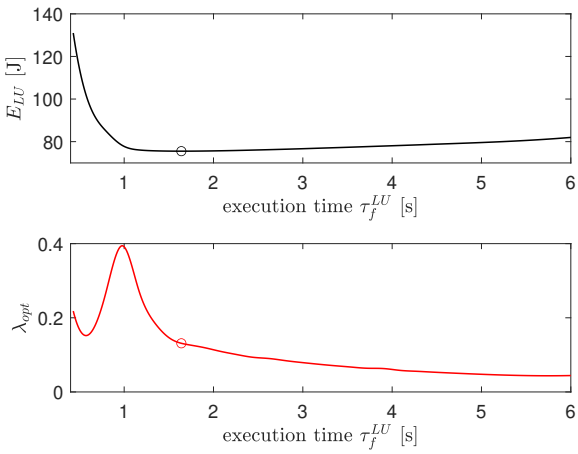

Fig. 2. Linear unit: power consumption E_{LU} and optimal λ value vs. execution time τ_f^{LU} of phase I

The first plot in figure 2 clearly shows the dependence between total execution time and energy consumption, and reveals that the energy vs. time curve can

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be ideally split into two regions. For execution times smaller than the optimal value, highlighted by the two circles, energy increases steeply as τ_f^{LU} is decreased, while for values of τ_f^{LU} larger than the optimal value, the energy requirement increases almost linearly. This is due to the different balance between two effects [10], i.e. the effect of the terms depending on speed and accelerations, and the effect of the motion-independent terms (such as those related to constant forces). Since the latter are quite pronounced in the test case under consideration, due to high static friction forces T_{eq} in (1), increasing too much the motion time is not beneficial in term of energy consumption.

These results refer to the first phase of motion, and hence they include the payload $m_L = 3\ kg$. The results of the application of the same method to the second phase of motion, when the linear unit does not carry any payload and is returned to the starting position, are very similar to the ones already displayed (and therefore are not shown): the contribution of the payload m_L is scarcely relevant on the dynamics of the linear unit due to the high reduction ratio implemented by the belt drive and the gearbox.

The Eco Motion Planning solution for the linear unit is therefore found by completing the first phase of motion in 1.64 s, while the second one is to be executed in 1.59 s, leading to a energy consumption over a cycle equal to 150.9 J. Both the optimal motion times are consistent with the total execution time which has been set in this example to be equal to 6 s. Two rest times are therefore required to ensure the imposed cycle duration.

4.2 SCARA robot

The classical SCARA robot with three DOFs is assumed, which is commonly used in pick & place operations given its high speed capabilities and for its good price/performance ratio. The robot is actuated by three brushless motors, that are assumed to be controlled by non-regenerative drives. The main parameters used to describe its dynamics are reported in Table 2

Table 2. Electric and mechanical parameters of the SCARA robot

Parameter	**Joint 1**	**Joint 2**	**Joint 3**
Link length	0.45 m	0.35 m	-
Link mass	14 kg	18 kg	2 kg
Gear ratio	1/30	1/30	1/30
Motor inertia	$1 \cdot 10^{-4}\ kgm^2$	$1 \cdot 10^{-4}\ kgm^2$	$1 \cdot 10^{-4}\ kgm^2$
Viscous friction coefficient	0.001 Nms/rad	0.001 Nms/rad	0.001 Nms/rad
Coulomb friction force	$2 \cdot 10^{-2}$ Nm	$2 \cdot 10^{-2}$ Nm	$2 \cdot 10^{-2}$ Nm
Motor winding resistance	3 Ω	3 Ω	3 Ω
Motor back-emf constant	0.375 Vs/rad	0.375 Vs/rad	0.375 Vs/rad
Motor torque constant	0.6 Nm/A	0.6 Nm/A	0.6 Nm/A
Peak motor torque	2.5 N	2.5 N	2.5 N
Peak motor power	75 W	75 W	75 W

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The aim of the EMP is to define an energy optimal motion profile for the robot when executing a pick & place task, from the prescribed initial position to a final one, and then back again to the initial one. In accordance with the payload of the linear unit already discussed, the robot payloads are equal to 0 and 3 kg in the first and second phase, respectively. The same via-points are assumed in the two phase (obviously with reverse order); different motion durations in moving from one point to the next one are instead adopted, since these intervals are exploited to optimize the energy consumption.

The evaluation of the energy consumption starts from the robot inverse dynamic model, that allows estimating the torque required to the robot actuators, $\mathbf{T}_j$, as a function of joint reference position, speed and acceleration, which are represented by $\mathbf{q}$ and its time derivatives:

$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}}(t) + \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}}) + \mathbf{g}(\mathbf{q}) + \mathbf{f}_v\dot{\mathbf{q}}(t) + \mathbf{F}_c sign(\dot{\mathbf{q}}(t)) = \mathbf{B}\mathbf{T}_j(t) \tag{12}$$

$\mathbf{M}$ is the mass matrix, while $\mathbf{C}$ and $\mathbf{g}$ account for, respectively, the Coriolis acceleration terms and the gravity effects. Friction contributions are split into a speed-dependent viscous term proportional to $\mathbf{f}_v$ and a constant term $\mathbf{F}_c$. Finally, $\mathbf{B}$ is the force distribution matrix. Once the torque to be provided by each motor is computed, the evaluation of energy consumption relies on the electro-mechanical model in Eqs. (2-4), by summing up the energy consumed by the three motors.

The goal of EMP is to minimize the energy consumption E_{robot} associated with the execution of the task, by solving a constrained nonlinear optimization problem. Solving this optimization problem becomes a rather simple task if a proper parametrization of the motion law, and hence of the cost function and of the bounds, is defined. Following a common approach, [42,43,44] trajectory design can be defined through the solution of an interpolation problem. This problem is set up by by defining of a sequence of N via-points to be visited in sequence by the robot, either defined in the joint space or in the operative space, which are then interpolated according to some trajectory primitives. The choice of the trajectory primitive is a topic which has drawn much attention in the last 30 years [45]; this issue is however outside the scopes of this chapter. A standard method, such as the "4-3-4 motion profile", is here used just to provide an example [42]. Without going into details, for which the reader can refer to [28], the motion of the end-effector of the robot is defined by a sequence of polynomial functions: the result is a coordinated motion of the robot that ensure exact interpolation of a set of pre-defined via-points with continuity up to acceleration.

In this case, the energy consumed by the robot, E_{robot}, can be parametrized through the the duration of each of the $N-1$ segments that connect the N via-points, τ_i. EMP for each phase is translated into the following optimization problem, that is parameteric with respect of the total execution time τ_f^R of each phase:

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$$
\begin{aligned}
&\min_{[\boldsymbol{\tau}]} E_{robot} \\
&\text{with: } \sum_{i=1}^{N-1} \tau_i = \tau_f^R \\
&\text{bounded } |\dot{\mathbf{q}}|, |\ddot{\mathbf{q}}|, |\dddot{\mathbf{q}}|; \\
&\text{bounded } |W_{e,j}|, |T_j|, \text{ with } j = 1, 2, 3;
\end{aligned} \tag{13}
$$

The design variables, i.e. the problem unknowns, are collected in the vector of motion durations $\boldsymbol{\tau}$, i.e. the motion times required for moving from one via point to another. As the pick & place motion comprises 6 via-points, $\boldsymbol{\tau}$ has 5 entries. The total execution time τ_f^R of each phase is assumed to be fixed, and therefore the optimization problem is parametric with respect of such a variable in both the phases. Additionally, hard bounds are set on the kinematic variables (speed, acceleration), on the motor power absorption $W_{e,k}$ and on motor torques T_j. Constraints on the jerk are set as well, to ensure smooth motion.

Figure 3 separately shows the optimized energy consumption of phase I and II, computed through the solutions of the problem in eq. (13), by assuming for both the phases the feasible durations. Such a plot reveals that feasibility is ensured for motion durations greater than 1.6 s and 2.6 s for the two phases respectively, since faster execution times are incompatible with the operative limits of the robot. Such a Figure 3 reveals that the increased payload in phase II leads to a convex shape of the energy consumption within the time domain of interest, ue to relevant constant loads, such as the ones related to the gravity force. This feature is consistent with the observations provided (and proved analytically with reference to a single-DOF system with constant inertia) in the work [10]. In contrast, the reduction of the energy consumption in phase I is achieved if the motion time is as long as possible. These results suggest that no rest phase should be assumed during the cycle lasting 6 s, and therefore the sum of the durations of the two phases will be 6 s, $\tau_{I,f}^R + \tau_{II,f}^R = 6$ s.

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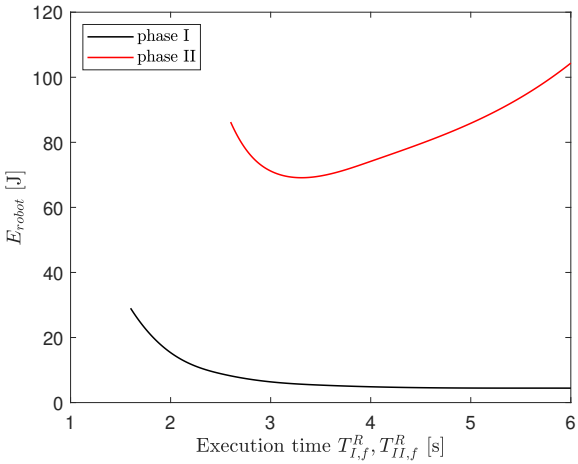

Fig. 3. Optimized energy consumption of the robot vs. total execution time: phase I and phase II

The total energy required by the robot to execute the whole task is plotted in Figure 4 as a function of the durations of the two phases $\tau^R_{I,f}$ and $\tau^R_{II,f}$ (with the constraint of a cycle time equal to 6 s). The minimum is achieved by splitting the total duration of the task, into a first phase that lasts $\tau^R_{I,f} = 2.81$ s and a second one that lasts $\tau^R_{II,f} = 3.19$ s. This choice sets the overall robot energy consumption to $E_{robot} = 76.4$ J that is the optimal value for the test case under investigation.

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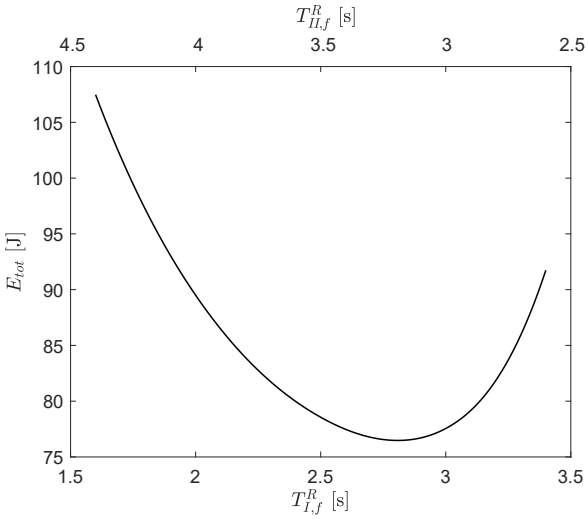

Fig. 4. Robot energy consumption for the whole task vs. phase I duration $\tau^R_{I,f}$ and phase I duration $\tau^R_{II,f}$

4.3 Analysis of the cell

In the light of the optimized motion profiles obtained for both the robot and the linear unit, the sequence of motions of the two cell components during the two phases of motion is optimally scheduled as shown in figure 5, which highlights the time frames in which the motion of the linear and of the robot happen, as well as the two rest phases of the linear unit.

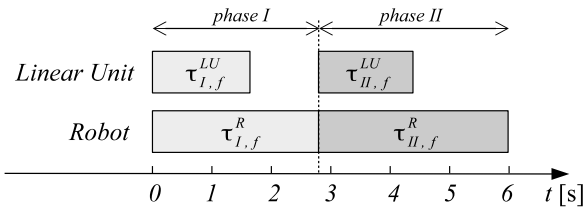

Fig. 5. Eco motion planning solution: scheduling of the motion phases

4.4 Analysis of the robot joint motion

The optimized motion solution is compared with a benchmark motion profile (hereafter denoted also as the "non optimized" one), obtained by using the standard "chord length distribution" to choose the distribution of the time intervals

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between two consecutive via-points. As for the distribution between phase I and II, assuming equal motion durations (3 s) for both the phases is not allowed, since the maximum motor torque exerted by the robot would violate the constraints set in eq. (13) during phase II . The duration of phase II has to be increased up to 4.3 s to obtain a feasible solution, thus the duration of the first one is to be reduced to just 1.7 s. The motion of the linear unit follows the same time frames, and it is not optimized as λ is set equal to 0.25 in both cases, as often done by practitioners, and no rest is assumed. The resulting energy consumption are 75.6 J and 78.6 J for the linear unit, 33.9 J and 78.2 J for the robot, by referring to the first and second phase, respectively. The overall energy consumption over a cycle is therefore equal to 267.3 J. Comparing this result with the optimized motion planning and scheduling reveals that an energy reduction equal to 14.8% is achieved, while ensuring the same productivity of the robotic cell. This is a clear evidence of the benefits of using EMP in designing and scheduling motions in a robotic cell. This saving is are expected to be even greater on a larger scale system, such as when focusing on a whole production line or even a whole plant.

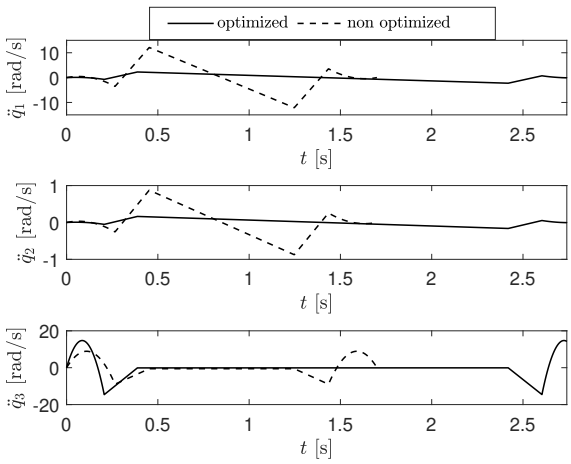

Fig. 6. Robot joint acceleration profiles, phase I: optimized vs. non-optimized solution

The obtained motion profiles are shown and compared in figures from 6 to 9, which show the acceleration profiles of the robot and compare the optimized with the non-optimized solutions. The relationship between joint accelerations and energy consumption is non obvious, suggesting that solutions based on heuristic approaches that discard the model of the energy consumption are usually hardly capable of leading to an energy-optimal solution.

The instantaneous values of the electric power drawn by each robot actuator are plotted as well in figures 8-9, which separately refer to each phase. Figure

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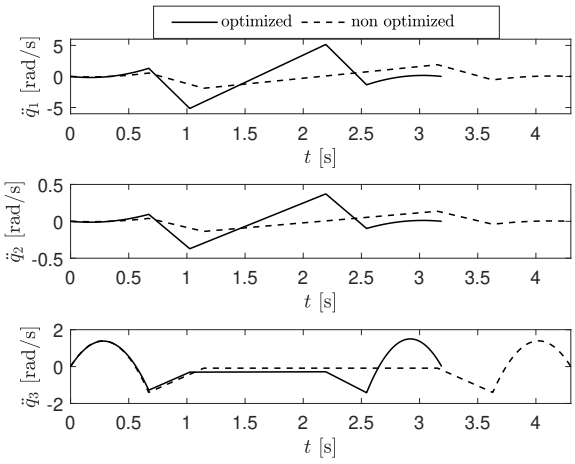

Fig. 7. Robot joint acceleration profiles, phase II: optimized vs. non-optimized solution

8 shows that the non-optimized motion is characterized by a pronounced power absorption as a result of its short duration, especially for the first two joints. Looking at figure 9, which refers to the second phase, it can be seen that, due to the longer execution time of the non-optimized motion, the power consumption is lower for joints 1 and 2 in comparison with the optimized solution. However this improvement is made irrelevant by the far worse energetic performance shown by the last joint. As the last joint carries a relevant payload during the last phase, with a relevant effect of gravity force, its duration should be, ideally, shorter.

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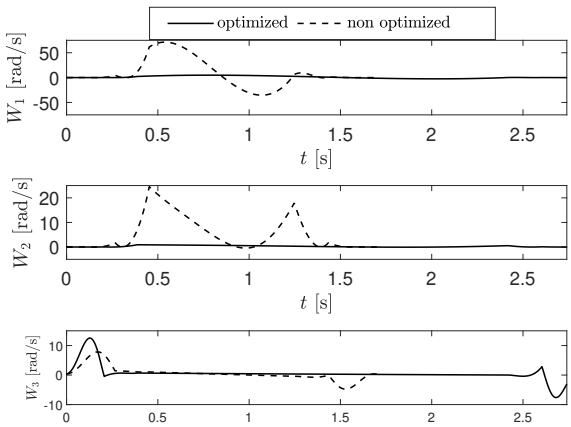

Fig. 8. Robot power absorbtion, phase I: optimized vs. non-optimized solution

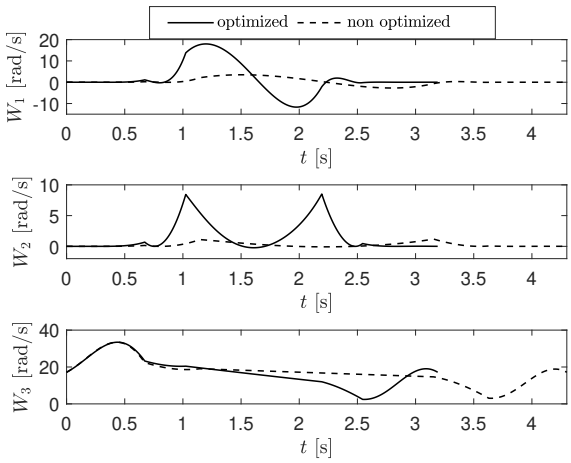

Fig. 9. Robot power absorbtion, phase II: optimized vs. non-optimized solution

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5 Conclusion

This chapter proposes, first of all, a literature review of the main methods used to improve the energy efficiency by means of motion design, the so-called Eco Motion Planning (EMP), that is one effective tool of eco-mechatronics. To allows the reader appreciating the benefits and the use of the techniques of EMP, a paradigmatic example is proposed and solved, together with the main models and equations to be adopted. The test case consists of a simple robotic cell, as those often adopted in manufacturing plants, that comprises a belt-driven linear unit, i.e. a single-DOF system with constant inertia, and a SCARA robot, as a representative example of a nonlinear multi-DOFs system. For both the systems involved in the robotic cell under study, an electro-mechanical model is developed and then used to reduce the overall energy consumption when executing two sequential tasks by optimizing some parameters of the motion profiles, that are some pillars of EMP: the motion time, the shape of the timing law and the motion scheduling. In particular, the application of the proposed method, that summarizes the features of some common state-of-the art techniques, allows defining the best distribution of the duration of each phase of motion and the best motion profile for each device. The outcome of the optimization procedure shows that a significant improvements of the energy consumption can be obtained, which is found equal to 14.8 % in comparison to a standard solution. This improvement is relevant as it can be obtained without any physical alteration of the setup or any modification of the cycle times. The method here discussed, as well as those proposed in the quoted literature, clearly shows how EMP is an essential step towards the development of sustainable mechatronic systems.

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