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Minimization of the energy consumption in motion planning for single-robot tasks

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Abstract

Recently, the importance of sustainable manufacturing has been widely discussed. The optimization of energy consumption in product manufacture has been deeply analyzed, mainly focusing on the energy directly absorbed by the manufacturing process. On the contrary, this paper focuses on the analysis and optimization of the energy consumption related to auxiliary robotic assembly processes, contributing to the identification of sustainable manufacturing strategies for pick and place robots. It proposes a methodology for the automatic generation of robot trajectories and the sequencing of the robot task, while minimizing the energy consumption. A probabilistic roadmap is created to identify a collision-free and minimum energy consumption trajectory for each couple of feasible tasks. Trajectory power consumption is evaluated exploiting dynamic information coming from the real robot motion planner using a model that takes into account the energy behavior of motors and drives and their operative conditions. A set of generated trajectories is selected, defining the task sequence and minimizing the robot cycle time. The differences between the results deriving by employment of the energy consumption minimization criterion versus time minimization criterion are presented through a simplified case.

Keywords: Motion planning; Energy consumption; Optimization

1. Introduction

During the last years, the rapid increase of the energy price together with strictly international and national policies has pointed out the problem of energy efficiency [1], moving companies' awareness from the reduction of the production time to the identification of an optimal trade-off between production time and energy consumption.

Since 1998, the energy consumption in the industrial sector has been reducing. For instance, in the US the manufacturing energy consumption decreased by 17% from 2002 to 2010 [2]. However, an unnecessary use of energy equal to 20-40% may still be found. This percentage is impressive considering a total EU-27 industrial energy use of 324 Mtoe (2004-2005) [3].

According to [4], for many industrial processes, *e.g.* the robotized spot-welding assembly, the consumption can be catalogued as "process energy" or "auxiliary energy". The process energy, generally representing the majority of the consumption, is the energy directly used in the manufacturing of the products, *e.g.* the assembly welding energy. The auxiliary energy is the energy required by the operations that allow the execution of the process, *e.g.* robotic energy consumption. Even if several papers cope with the reduction of the process energy [3], auxiliary energy plays a relevant role and deserves to be studied.

In [5], the relevance of the energy consumption reduction in robotic operations is underlined. The paper deals with the optimal placement of a path in the robot workspace so that the energy consumption is minimized coping with geometric, kinematic and dynamic constraints. [6] provides a methodology able to determine robot velocity and acceleration in order to minimize the energy consumption when moving from a starting point to a target point in a predetermined amount of time. Similarly, in [7], the influence of robot movement parameters on energy consumption is presented, focusing on robot optimal speed, acceleration and

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jerk. A more comprehensive approach can be found in [8] with reference to the automobile industry, where the electrical energy consumed by robotic application is about 8%. In this approach, several strategies to save energy for medium and high payload robot are presented: speed and acceleration variation along the robot path, fly-by trajectories and intelligent management of robot breaks. The same attention to energy saving is presented in [9], where an approach for reducing energy consumption of pick-and-place industrial robot is described. As in the previous approaches, the idea is to reduce the total energy consumption by means of constant time scaling, staring from pre-scheduled trajectories. An evolution of this paper can be found in [10], where the modeling and optimization of energy consumption in cooperative multi-robot is proposed. Specifically, the robots are coordinated through the variation of the velocities and acceleration along predefined path. The task execution sequence changes accordingly to the minimization criterion.

This paper proposes a completely different approach. Indeed, the idea is to allow the selection of the collision-free paths to move from a starting point to a target point that minimizes the energy consumption, while considering technological and geometrical constraints. The modification of the robot velocity and acceleration along all the selected paths is not included in this paper, but represents a future work. Moreover, the paper also take into account the whole robot motion plan, i.e. all the trajectories for the execution of several robot tasks have to be defined. Thus, in this paper, a method able to provide a single-robot motion plan minimizing the comprehensive energy consumption is presented, while taking into account robot cycle time.

The paper is structured as follows: in Section 2 the industrial problem is described; Section 3 presents the methodology, while Section 3.1, 3.2 and 3.3 describe in details the three steps of the approach: trajectory generation, robot dynamic and energy assessment, and task sequencing; in Section 4 the test case is presented and discussed; finally, conclusions and future works are driven in Section 5.

2. Problem statement

The paper focuses on the robot energy consumption in pick-and-place tasks. A task consists in the grabbing or release of an object in a specific position, thus representing a constraint to the robot configuration during the task execution. In such a context, two main problems have to be faced: the definition of collision-free trajectories among the tasks (couples of tasks) and the task execution sequence.

These two problems are interconnected since the execution sequence, apart from existing precedence constraints among the tasks, depends on the trajectories definition. In other words, task sequence may not be completely predefined, *i.e.* the final task sequence has to be optimized taking into account the energy consumption, the required cycle time and possible precedence constraints among the tasks. This optimization may lead to different results, if different trajectories are considered. In such a context, the optimization of the energy consumption and the cycle time generally represent a trade-off [9].

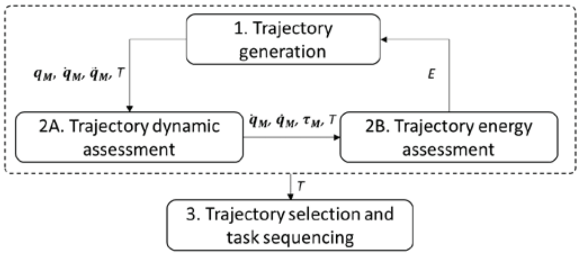

Figure 1: The approach

Worthy, the energy optimization is of upmost importance for pick and place tasks, where only the start and goal configurations are constrained.

3. Methodology

The proposed approach is based on three steps (Fig. 1). The first step (Section 4 - *Step 1*) concerns the generation of the trajectories. Specifically, for each couple of tasks (two tasks that could be executed one after the other), a collision-free trajectory minimizing the energy consumption is defined. The generation of the trajectories exploits the probabilistic roadmap technique [11] and the Open Robot Realistic Library (ORL) [12] provided by COMAU. The ORL library represents the virtualization of the real robot controller, according with the standard RCS [13], providing the robot interpolator and all the functionalities related to the robot dynamic model. The trajectories generated by the ORL are expressed in terms of motor positions q_M, velocities $\dot{q}_M$, and accelerations $\ddot{q}_M$. The minimization of the energy consumption is based on the employment of probabilistic roadmaps that allow the identification of the best geometrical path, along which the joint velocity and the acceleration are maximal.

The evaluation of the energy consumption derives from *Step 2* where the dynamic and energy assessments of the robot trajectory occur. On the basis of the information coming from Step 1, together with the dynamic model of the specific robot and the embedded dynamic parameters, the ORL is responsible of the trajectory dynamic assessment (Section 3.2.1 – *Step 2A*). On the contrary, the trajectory energy consumption E (Section 3.2.2 – *Step 2B*) is provided by an ad-hoc developed model that is able to predict the energy consumption according to the trajectory duration T, velocities $\dot{q}_M$ [rad/s], acceleration $\ddot{q}_M$ [rad/s^2] and torque τ_M [Nm].

The last step of the approach (Section 3.3 - *Step 3*) concerns the definition of the task sequence, thus the selection of the trajectories. Since the cycle time is often a relevant factor, the idea is to define the final sequence selecting the trajectories so that the cycle time is minimized. In such a way, a trade-off between the energy consumption and the cycle time is reached.

3.1. Step 1: Trajectory generation

During trajectory generation, collision-free path has to be calculated within the robot family of tasks. In this activity, three factors have to be considered: the degrees of freedom