Optimization methods of the industrial robots' trajectory

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Abstract. In this paper, we present a part of our wider research regarding modeling, simulation and optimization of the trajectory of the industrial robots. After a short introduction on the importance of the industrial robots, the necessity and widely interest regarding the trajectory optimization, we present a classification of the optimization methods: numerical, computational and hybrid. Then, we make a brief presentation of the main optimization criteria approached in the last few years in several scientific papers, regarding the optimization of the industrial robots' trajectory.

1. Introduction

In the last decades, the industrial robots are more and more used across all industries, and across all types of companies, from the small and medium-sized companies to the large companies, in special in automated production processes, where the companies seeking agile production methods. Taking into consideration the important role of the robots in the present and future industrial processes, there are a lot of studies in robotics on increasing performance, precision and flexibility, and reducing the effort, time, energy and cost, through streamline and optimize the trajectories and the motions of the industrial robots [1].

Generally, optimization aims at establishing, based on one or more predetermined criteria, the best solution, called the optimal solution, for a given situation, when several variants are possible. In the current context, optimization of processes of any kind, in this case of engineering, is considered as of particular importance, as evidenced by a huge volume of research, publications and scientific events dedicated to this subject.

2. Optimization methods

Optimization methods can be categorized by several criteria. Thus, from the point of view of the restrictions imposed on the variables, there are problems of optimization without restrictions and with restrictions. After the kind of objective function, there are linear optimization problems, in which both the objective function and the restrictions are linear, and nonlinear optimization problems [2]. There are multimodal optimization for functions with multiple global or local optima, multicriteria optimization when there are multiple optimization criteria that are conflicting, optimization in dynamic or non-deterministic environments.

2.1. Numerical optimization methods

In a mathematical sense, optimization is a process of minimizing or maximizing an objective function, and at the same time satisfying some constraints or restrictions. There are standard optimization techniques and algorithms, which are found in most of the specialized literature. There are also some more modern approaches that combine mathematical rigor with engineering practice, such as, for example, linking the analytical character of an optimization problem expressed in terms of optimality, and analyzing numerical algorithms optimization used to solve the problem [3].

The numerical methods used in engineering [4] to resolve optimization problems are divided into two major classes: direct methods and indirect methods. Direct methods are most often used because they are easier to configure and resolve, but they do not lead to precise solutions. Indirect methods are more difficult but provide very good precision, which is why they are used in certain applications that require a precise solution. In solving the optimization problems are used: systems of nonlinear algebraic equations (on indirect methods), differential equations and integration of functions (both indirect and direct methods) and nonlinear programming methods, namely gradient methods and heuristic methods (to direct methods). Lately, in optimization issues are used combinations of direct and indirect methods in a so-called hybrid approach [5].

The main features of an optimization problem are:
- the decision variables, which can be selected from a certain set
- the objective function, which must be minimized or maximized
- the constraints or restrictions to be observed, by equality and/or inequality.

2.1.1. Optimization without constraints. To solve optimization problems without constraints, numerical methods of decreasing (relaxation) are used, namely, methods that lead to decreasing the value of the objective function at each iteration and which, depending on the algorithms used, are classified as follows:

- one-dimensional optimization methods, or zero-order optimization, that only require the calculation of the objective function values at the current point and possibly at some neighboring points and are based either on direct, cyclical search, by coordinate axis directions, or random (the golden section search method, the bisection method, the Fibonacci sequence method, the Newton-Raphson classical method and the secant method, Hooke-Jeeves, the Nedler-Mead simplex method), or on the approximation of the objective function with a polynom determined by interpolation using the function values and/or the derivatives of the objective function at certain points (quadratic interpolation in two or three points and cubic interpolation).

- first order numerical optimization methods or linear search methods, based on the information obtained from the valuation of the objective function and its gradient (gradient method or steepest descent method, conjugate direction method, variable metric methods). These linear search methods are very much used in practice because they make a favorable compromise between simplicity and efficiency.

- second-order numerical optimization methods or Newton type, more complex, because they use information about the curve of the objective function or the Hessian matrix (the Newton or Newton-Raphson method and the quasi-Newton method).

- numerical methods to optimize some objective functions with special structure, to the type of the least squares (Gauss-Newton method and Levenberg-Marquardt method).

2.1.2. Optimization with constraints. When solving optimization problems with constraints, are used:
- first- and second order methods for nonlinear programming with convex constraints (descending direction methods - conditional gradient method and projected gradient method - and the projected Newton method).

- optimization methods for nonlinear programming with equality constraints (methods for quadratic programming with equality constraints, Lagrange's first order method, Lagrange-Newton method, Newton method with equality constraints).

- optimization methods for general nonlinear programming (active-set methods, sequential quadratic method, penalty methods, barrier methods, interior point methods). Of these, interior point methods are considered as a modern alternative to others and have the advantage of replacing non-smooth conditions with a set of smooth conditions, which are an approximation of the original ones.

2.2. Computational optimization methods
Often, optimization in engineering is doing by default for relatively simple problems, on the base on own knowledge and experience, the engineer trying to find an optimal model, through several attempts, in an iterative process, using certain software packages for modeling and analysis. To solve more complex problems, are used algorithms and programs capable to automate optimization, and the computer is used both to evaluate the model and to find a better solution in a shorter timeframe. Solving a computational optimization problem requires the following steps: description of the problem, discussion of the problem, defining the optimization problem, model development, ordering the equations, coding the model, possibly debugging it, linking the model with the optimization software and checking, optimizing the model [6].

There are some difficult optimization problems for both people and computers, problems characterized by a large search space, processes that are carried out in complex or dynamic environments, etc., so-called "bad" problems. In these situations, are used calculus and optimization methods based on computational intelligence, "Computational Intelligence" or "Soft Computing". It is about the neural calculus, the evolutionary calculus, and the fuzzy calculus, which use the artificial neural networks, the evolutionary algorithms, and the fuzzy system as the working tools, inspired by the human brain, the processes of evolution in nature and the specifics of human reasoning and language natural. This new style of calculus is based on fuzzy logic and several artificial intelligence tools: Probabilistic Reasoning, Genetic Algorithm, Evolutionary Programming, Neural Networks, and Machine Learning [7, 8].

If artificial intelligence is considered the pioneer, computational intelligence is the successor. Thus, if in the artificial intelligence is considering that the expert is putt into the computer, in the case of computational intelligence there is a collaboration between the expert and the computer [9].

2.3. Hybrid optimization methods
As even some of the most modern methods may be inadequate in some situations, it has been tried and proven by studies that the shortcomings of a method can be removed by incorporating specific techniques of another method, complementary. Thus, by combining concepts and algorithms from two or more methods, can be created a new, hybrid method with superior behavior. An example of such a hybrid method is obtained by combining genetic algorithms that excel in exhaustive exploration of an area of a problem, but are deficient in local refining of promising solutions, with algorithms such as Pattern Search (PS) that offer a highly effective local optimization but they are not able to explore the whole field. The new hybrid method thus obtained has both global optimization capabilities provided by the genetic algorithms, and local optimization capabilities provided by the Pattern Search numerical algorithms [10].

3. The industrial robots' trajectory optimization
In engineering, a problem of optimization means to minimize or maximize a function, that is subject to constraints, that, mathematically, can be inequalities or equations, the optimization problem being called the nonlinear programming problem [11]. The aim of the industrial robots' trajectory optimization is to minimize or maximize at least one of the following objective functions:
- to minimize the execution time, respectively to maximize the robot productivity, taking into consideration the limits of the relative speeds of the actuators' elements
- to minimize the energy consumption or mechanical work needed for execution
- to minimize the maximum power necessary for operating the robot
- to minimize the maximum forces and moments necessary for actuation.

To get better results, many times is achieved multi-criteria optimization, when the objective functions that have to be minimized or maximized express simultaneously combinations of more criteria.

As presented in detail in [1], and illustrative in figure 1, the most common optimization criteria used for industrial robots' trajectory optimization, after a review of 40 scientific papers in this area, are:
- minimum time trajectory planning (7)
- minimum energy trajectory planning (12)
- minimum jerk trajectory planning (1)
- multi-criteria optimization (14): minimum time and minimum cost; minimum time and minimum energy; minimum time and continuous jerk; time-optimal and jerk-bounded; time-jerk optimal; weighting between the execution time, acceleration, and jerk; minimum transmission time and maximum load carried; minimum of the Euclidean distance between the target positions and minimum effort of the servomotors; optimal speed-trajectory length; optimization of the singularities, joint limits and collisions; optimization of six objective functions: weighted balance of traveling time, actuator torques, singularities avoidance, joint jerks, joint accelerations and gripping force.
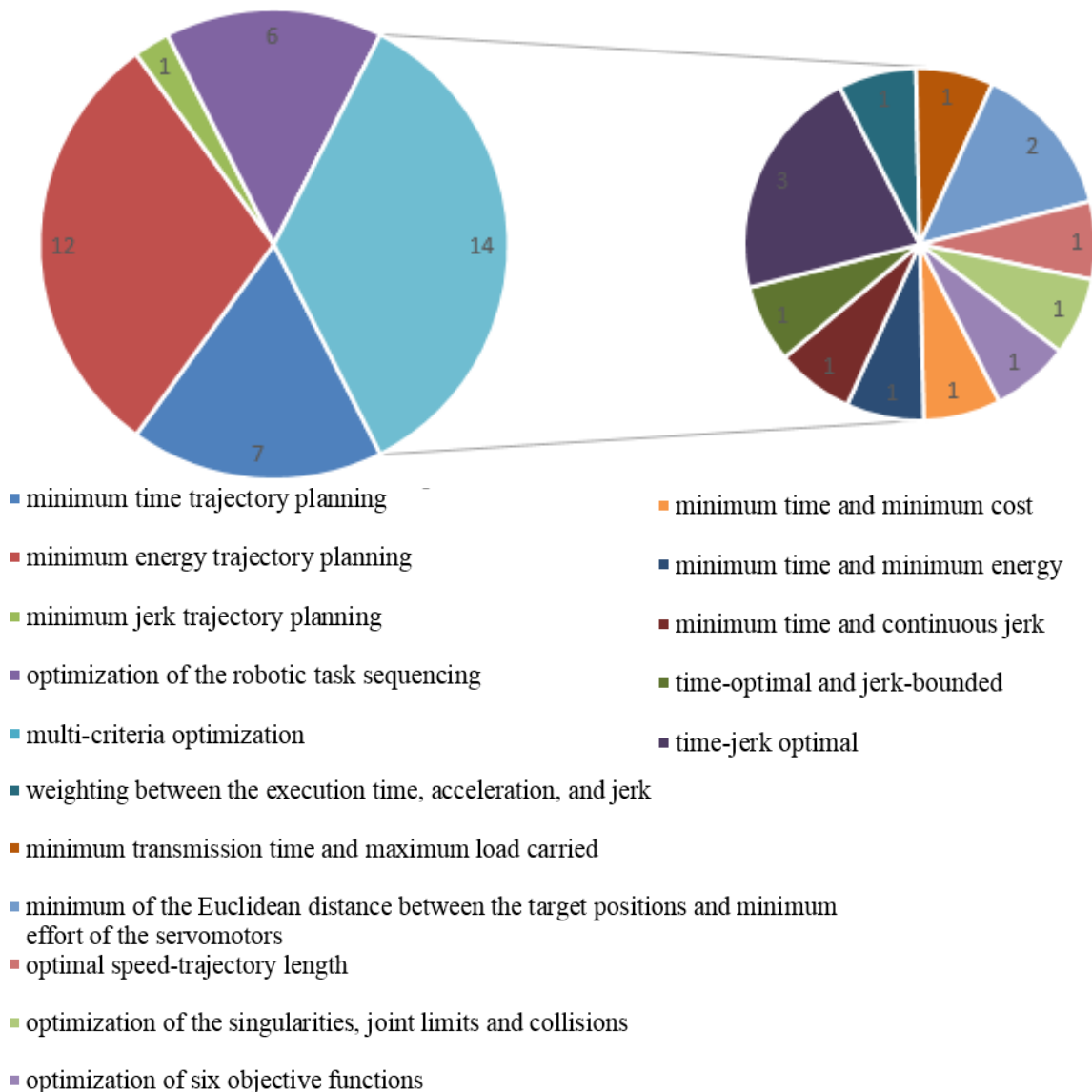- optimization of the robotic task sequencing (6).

■ minimum time trajectory planning

■ minimum energy trajectory planning

■ minimum jerk trajectory planning

■ optimization of the robotic task sequencing

■ multi-criteria optimization

■ weighting between the execution time, acceleration, and jerk

■ minimum transmission time and maximum load carried

■ minimum of the Euclidean distance between the target positions and minimum effort of the servomotors

■ optimal speed-trajectory length

■ optimization of the singularities, joint limits and collisions

■ optimization of six objective functions

■ minimum time and minimum cost

■ minimum time and minimum energy

■ minimum time and continuous jerk

■ time-optimal and jerk-bounded

■ time-jerk optimal

Figure 1. Optimization criteria of the robots' trajectory.

In the process of optimization in virtual modeling, an accurate parametric model of the mechanical system is very important [12], especially in the case of tasks control, the positioning accuracy, and the robot calibration [13].

4. Conclusion

The optimization of any kind of processes, including those in engineering, is today particular importance, this being demonstrated by a large interest dedicated to this topic. How, in the present, the industrial robots are used on a more and more wider scale, across all industries, searching the optimal trajectories is a complex and difficult task, assumed by researchers and specialized companies in many kinds of approaches. This work is integrated into this current, and represent a part of wider research developed by us regarding modeling, simulation, and optimization of the trajectory of the industrial robots.

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