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Optimum static balancing of an industrial robot mechanism

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Abstract

Force balancing is a very important issue in mechanism design and has only recently been introduced to the designing step of robotic mechanisms. In creating the best robot design, the statical balancing plays a vital role because it reduces the required motor power. To get a simple and more-effective control system, elimination or significant reduction of the gravity load at a powered joint is an important one. With utilization of these objectives an optimization problem is formulated. The average force on the gripper in the working area is taken as an objective function. The design variables are lengths of the links, angles between them and stiffness of springs. This paper describes the use of conventional and evolutionary optimization techniques such as Newton's method (NM), conjugate gradient method (CGM), Genetic Algorithm (GA), Elitist Non-dominated Sorting Genetic Algorithm (NSGA-II) and differential evolution (DE) to solve the above problem. An industrial robot with 6-degree-of-freedom (6-DOF) (APR 20) is considered as a numerical example. The robot has a spring balancing system that has to be optimized. The existing optimization model is improved by adding two new variables. Also, a comprehensive user-friendly general-purpose software package has been developed using VC++ to obtain the optimal parameters using the proposed DE algorithm. The methods used in this article can be applied to find out solutions for a wide range of similar problems without further simplifications.

Keywords: Static balancing; Robot mechanism; NM; CGM; GA; NSGA-II; DE

1. Introduction

This paper addresses the static balancing of a 6-degree-of-freedom (6-DOF) industrial manipulator (APR 20). Static balancing is defined as the set of conditions on mechanism dimensional and inertial parameters which, when satisfied, ensure that the weight of the links does not produce any torque (or force) at the actuators for any configuration of the mechanism, under static conditions. Static balancing leads to considerable reduction in the actuator torques (or forces), which in turn allows the use of less powerful actuators and therefore leads to more efficient designs. Hence, the balancing conditions are very important in a context of design of robot mechanism.

Static balancing means that the weight of the links does not produce any force at actuators for any configuration of the manipulator. When a robot is statically balanced, its potential energy is constant for all possible configurations. Two methods are studied in literature for the static balancing are using counterweights (CW) and using springs. The balancing by masses is due to added CW or due to link's mass redistribution. In case of balancing by springs, changes in the mass and inertia parameters of the robot mechanism is insignificant because the weight of the built-in springs or cylinders are very less compared to the link weight. This is the main advantage of the balancing by springs. In certain cases, combination of both spring balancing and mass balancing (especially mass redistribution of the links) may be better.

A publication by Herder (2002) discusses the scope of research work in the application of static balancing in parallel mechanisms. Graphical optimization methods such as contour tracing and field fitting are used in that publication. Santangelo and Sinatra (2005) described two methods for static balancing of a 6-DOF parallel platform-type manipulator using CW and using springs. They found

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that spring balancing system is best one. But their method did not lead to optimal static balancing system. An illustration by Imme Ebert-Uphoff et al. (2000) described static balancing for improving the performance of parallel platform manipulators, being used as motion bases in commercial flight simulators, where the weight of the cockpit results in a large static load. But, they have not presented any procedure to do optimal static balancing while improving the performance of the system. Ouyang et al. (2003) described an integrated approach to design a real-time controllable (RTC) mechanism considering force balancing and trajectory tracking, simultaneously. A force balancing method called Adjusting Kinematic Parameters (AKP) for robotic mechanisms or RTC mechanisms is proposed by Ouyang et al. (2005), as opposed to the CW force balancing method. A comparison of the two methods, namely the AKP method and the CW method, is made for two RTC mechanisms with different mass distribution. The joint forces and torques are calculated for the trajectory tracking of the RTC mechanisms. The result shows that the AKP method is consistently better than the CW method in terms of the reduction of the joint forces and the torques in the servomotors, and the smoothing of the fluctuation of the joint force. But the AKP method does not do the static balancing and trajectory in an optimal way. An optimization problem is formulated to find suitable design variables for balancing mechanisms of a robot. Kalker-Kalkman (1991) solved this problem by using Monte Carlo simulation with interactive interval reduction.

Any conventional non-linear optimization method like Monte Carlo simulation (Kalker-Kalkman, 1991) and Graphical optimization methods (Herder, 2002) can be attracted by local minima. In order to overcome this problem, the process should be started from various initial guesses. Also, the conventional technique involves computing the gradient and the Hessian of objective function and constraints which implies that continuity of second order must be ensured. However, traditional techniques cannot solve discontinuous terms (e.g., frictions) in physical models. Non-conventional optimization techniques can be used to overcome the above drawbacks. Using the non-conventional optimization techniques such as Genetic algorithm (GA), encouraging results have been already obtained in the treatment of discontinuous physical models (Segla et al., 1998). The advantages of evolutionary techniques are: (1) population-based search, where global optimal solution is possible; (2) no need of any auxiliary information like gradients, derivatives, etc.; (3) complex and multimodal problems can be solved for global optimality; (4) problem independent, i.e., suitable for all type of problems.

A general procedure for optimal static balancing of an industrial robot ABR20 with 6-DOF is formed and demonstrated by Segla et al. (1998). Their method is based on spring balancing method. The problem is solved using GA. The average force on the gripper is considered as an objective function to be minimized. The design variables are length of links, angles between them and spring stiffnesses. In an ideal static balancing system, the average of all forces on the gripper is zero in the working area of the robot.

In this paper, the existing optimization model (Segla et al., 1998) is improved by adding two new variables. Also the importance of the new variables is dealt with. This paper describes the use of conventional and evolutionary techniques such as Newton's method (NM), conjugate method (CM), GA, Elitist Non-dominated Sorting Genetic Algorithm (NSGA-II) and differential evolution (DE) to solve the improved optimization model. An industrial robot with 6-DOF (APR 20) is considered as a numerical example. The robot has a spring balancing system that has to be optimized. The method described here can be applied to any robot or mechanism that has to be designed to produce a certain kinematic, static or dynamic behavior. Also, a comprehensive user-friendly general-purpose software package has been developed using VC++ to obtain the optimal parameters using the proposed DE algorithm.

This paper is organized as follows. In Section 2, the proposed NM, CGM, GA, NSGA-II and DE techniques to obtain the minimum average force on the gripper in the working area are presented. In Section 3, a numerical example, the industrial robot with 6-DOF (APR 20) is presented to illustrate the use of the proposed GA, NSGA-II and DE techniques to find out the objective function. In Section 4, the results obtained in various methods are presented and compared. The conclusions are presented in Section 5.

2. Proposed methods

In this section, five conventional and evolutionary optimization techniques used for obtaining minimum average force on the gripper in the working area are described.

2.1. Conventional techniques

The solver for NM and conjugate gradient method (CGM) available in MS Excel 2003 software has been used for solving the problem. The sample pages of solver with all information are shown in Figs. 1 and 2. In NM, the second-order derivative information (called Hessian matrix) is used to find a search direction. Even though the search direction is not guaranteed to be a descent direction, for points close to the true minimum point, this method is very efficient. This method is also the best for positive objective functions.

CGM (Fletcher–Reeves method) creates search directions that are conjugate with respect to the objective function. Conjugate search directions are found using first-order derivatives. This method is best for linear or quadratic objective functions. This method is most popular among all direct search methods. Starting point plays a