Modeling and design optimization of a robot gripper mechanism

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ABSTRACT

Structure modeling and optimizing are important topics for the design and control of robots. In this paper, we propose a process for modeling robots and optimizing their structure. This process is illustrated via a case study of a robot gripper mechanism that has a closed-loop and a single degree of freedom (DOF) structure. Our aim is to conduct a detailed study of the gripper in order to provide an in-depth step-by-step demonstration of the design process and to illustrate the interactions among its steps. First, geometric model is established to find the relationship between the operational coordinates giving the location of the end-effector and the joint coordinates. Then, equivalent Jacobian matrix is derived to find the kinematic model; and the dynamic model is obtained using Lagrange formulation. Based on these models, a structural multi-objective optimization (MOO) problem is formalised in the static configuration of the gripper. The objective is to determine the optimum force extracted by the robot gripper on the surface of a grasped rigid object under geometrical and functional constraints. The optimization problem of the gripper design is solved using a non-dominated sorting genetic algorithm version II (NSGA-II). The Pareto-optimal solutions are investigated to establish some meaningful relationships between the objective functions and variable values. Finally, design sensitivity analysis is carried out to compute the sensitivity of objective functions with respect to design variables.

1. Introduction

Robot design is a very complex process involving great modeling and simulation efforts. It has suffered an important progress in the last decades and many approaches deal with this issue. Major steps in robot manipulator design are; kinematics design, dynamics design, thermal design, and stiffness design [1]. In particular, robot modeling and structural analysis are required in all industries. To address these requirements, a design process is proposed in this paper that combines both; robot modeling and geometrical optimization. The proposed process is a sub-process of the general robotics design process in which modeling and optimization activities play essential and complementary roles in the design. As an illustrative case study, we carry out a modeling and an optimal design of a planar single degree of freedom (DOF) mechanism that is used for robot hands or grippers. These kind of mechanisms are amply used because of its simplicity and it only needs one actuator to move it, so many robots use this kind of mechanisms as gripper. However, many researches deal with geometric, kinematic, and dynamic modeling of the robots using different techniques. Some others work on optimization methods for multicriteria robot design optimization. A survey of these research works is presented in the following paragraphs.

Modeling is essential for design specifications, simulation, and advanced control of robots. Different techniques of modeling are available for modeling robots, especially for parallel and closed-loop robots due to their complexity [2–5]. Ibrahim and Khalil presented kinematic and dynamic modeling of three degrees of freedom 3-RPS (revolute, prismatic, and spherical) parallel robot [6]. This robot is characterized by a coupling between the 6-DOF of the platform. After presenting a (6×3) kinematic Jacobian matrix, they developed a reduced (3×3) Jacobian matrix relating the linear velocity of the platform with respect to the three actuated joints. In another paper, Khalil and Guegan presented closed form solutions for the inverse and direct dynamic models of the Gough-Stewart parallel robot. The models are obtained in terms of the Cartesian dynamic model elements of the legs and of the Newton-Euler equation of the platform [7]. Andrzej et al. used forward and inverse kinematic problem as well as working space and strength analysis issues for the construction of 3-DOF tripod electro-pneumatic parallel manipulator [8]. Qin et al. proposed analytical modeling of a two-staged parallel mechanism composed by a rigid platform in a serial connection with a compliant platform [9]. Hassan and Abomoharam performed a study of a gripper that has two closed loop structure. After finding geometric and kinematic models, they determined the geometrical solution space and verified it via a CAD
model of the gripper [10]. Ha et al. employed Hamilton’s principle, Lagrange multiplier, geometric constraints, and partitioning method to derive the dynamic equations of a slider-crank mechanism. They showed that dynamic formulation could give a good interpretation of a slider-crank mechanism by comparing the numerical simulations with experimental results [11]. Özgür and Mezouar exploited screw theory expressed via unit dual quaternion representation and its algebra to formulate both the forward (position and velocity) kinematics and pose control of an n-DOF robot arm [12].

Different researches of the optimum design of robot manipulators are available in the works of [13–16]. Xie et al. proposed a decoupled 3-DOF parallel tool head without parasitic motion. Using the atlases of the tool architecture as bases, the optimal kinematic design of the tool head is carried out [17]. Jiange et al. presented a dynamic modeling and redundant force optimization of a 2-DOF parallel kinematic machine with kinematic redundancy in order to minimize the position errors of the manipulated platform [18]. Nevertheless, in real robot design problems, the number of design parameters can be very large, and their influence on the value to be optimized (the objective function) can be very complicated, having a strongly non-linear character. In these complex cases, stochastic optimization techniques including evolutionary algorithms such as genetic algorithms (GA) may offer solutions to the problem [19]. Coello et al. proposed GA-based multiobjective optimization hybrid technique to optimize the counterweight balancing of a robot arm [20]. Jamwal et al. used a modified genetic algorithm to optimize the kinematic design of a parallel ankle rehabilitation robot [21]. Oszczeka and Krench discussed some new methods for multicriteria design optimization using evolutionary algorithms. The main aims of these methods is to reduce the computing time and to facilitate the decision making process. Examples of a robot gripper mechanism and a clutch break design are presented in this paper showing that these methods can be used to solve different design optimization problems [22]. Gao et al. described the implementation of genetic algorithms and artificial neural networks as an intelligent optimization tool for the dimensional synthesis of the spatial 6-DOF parallel manipulator. The multi-objective optimization (MOO) problem was consisted of two functions: system stiffness and dexterity, which are derived according to kinematic analysis of the parallel mechanism [23].

The rest of the paper is organized as follows. The proposed modeling and optimal design process of the robots and its advantages are described in Section 2. In Section 3, our case study of a robot gripper mechanism is described and its geometric modeling is recalled. Section 4 reviews the kinematic modeling of the gripper, then, the dynamic model is derived in Section 5. After describing and modeling the gripper, the corresponding multi-objective optimization problem is formalized in Section 6. Section 7 describes the solution algorithm of the optimization problem, and the non-dominated sorting genetic algorithm version II (NSGA-II), it discusses the results. Section 8 presents the sensitivity analysis of the gripper mechanism design. Finally, Section 9 summarizes the contributions and results made in this paper and gives some perspectives.

2. Modeling and optimal design process

The design of robots is a complex engineering task, in which certain mathematical models are required. This task can often be seen as an optimization problem in which the robot parameters or structure describing the best quality design is sought. In this paper, an integrated modeling-optimizing robot design process is proposed where the modeling steps are combined with the optimal structural design process, Fig. 1 illustrates this proposed process. During this procedure, the geometric information is transferred from one step to the next step. The modeling stage information is captured as input by the optimization stage, while the optimal design information feeds back the modeling stage. These interactions give the designer the advantage to better define the design parameters and to take into account both the modeling and the optimization issues in one integrated process. These two issues are often handled separately as presented in the literature survey above, but in our presented process, they are combined together in order to benefit of their complementarity.

The process starts by defining the problem that must be solved. Depending on the objectives of the study, the applied steps may vary; it could be finding the geometric, kinetic, or dynamic models of the robot using different techniques. These models are important to apply high performance control algorithms, to improve stiffness, to increase payload, to improve force/torque capacity, etc. The objective could be also finding the optimal design that aims at enhancing the performance indexes by adjusting the structural parameters, such as the geometrical lengths. In the optimal design, several performance indices are involved, such as stiffness, transmission ratio, and accuracy.

The modeling stage starts by the geometric modeling, which represents the relations between the location vector of the end-effector $X$ and the joint coordinate vector $q$ (Eq. (1)). Several methods and notations have been proposed to find the geometric model; the most widely used one is that of Denavit-Hartenberg [24]. However, this method is developed for simple serial-structured robot. Khalil and Kleinfinger have proposed a unified description of parallel and tree-structured robots [25].

$$X=f(q)$$

Kinematic model is to find the relation between the end-effector velocity and the joint velocities. Kinematic model could be written using the Jacobian matrix $J$. This matrix appears in calculating the derivation of the geometric model. It gives the differential variations of the operational coordinates $X$ in terms of the differential variations of the joint coordinates $q$ (Eq. (2)). For parallel manip-
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