



Research paper

Serial vs. quasi-serial manipulators: Comparison analysis of elasto-static behaviors

Alexandr Klimchik^{a,*}, Anatol Pashkevich^{b,c}^a Innopolis University, Universitetskaya St, 1, Innopolis, Tatarstan, 420500, Russia^b Ecole des Mines de Nantes, 4 rue Alfred-Kastler, Nantes 44307, France^c Institut de Recherches en Communications et en Cybernétique de Nantes, UMR CNRS 6597, 1 rue de la Noe, 44321 Nantes, France

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ABSTRACT

The paper deals with comparison of industrial manipulators of serial and quasi-serial architecture. It proposes a new methodology that is based on estimation of the robot accuracy for three typical manufacturing tasks that are optimally located within the robot workspace. To cover wide range of applications, the set of isotropic, quasi-isotropic and extended benchmark tasks are considered and relevant compliance errors are evaluated taking into account the end-effector deflections caused by the external forces. It is shown that regardless of the benchmark task, the serial manipulators are preferable for small and medium tasks while the quasi-serial ones' better suit to large-dimensional tasks only. The proposed technique was applied to the architecture comparison analysis of 15 industrial robots of both serial and quasi-serial manipulators with similar working radius and payload about 200 kg.

1. Introduction

Recent advances in the manufacturing technologies and enhancement of robot performances extend robots applications from traditional pick-and-place and welding operations [1–4], to machining where robotic manipulators are subjected to essential external loading caused by tool-workpiece interaction [5–7]. Nowadays, industrial robots rapidly take their niche in the drilling [8,9], milling [10,11], friction stir welding [12,13] and other operations [14–16], progressively replacing in these areas less flexible and more expensive CNC machines. Nevertheless, the robot positioning accuracy under the external loading remains rather limited, and practicing engineers face the problem of well-grounded robot selection from the big variety of industrial robots provided by manufactures [17–19]. To help the final user, this paper proposes an engineering technique that deals with comparison of robot architecture and their basic parameters taking into account influence of the external loading generated by the technological operation.

To improve robot accuracy under the loading, there were developed different online and off-line methods [20–25] allowing reducing the impact of the manipulator deformations on the manufacturing quality. The most efficient technique is based on the online tracking of robot position and compensation of related deflections [26]. This approach is able to compensate errors of different nature (not only compliant ones, but also non-calibrated geometric and non-geometric errors), but it requires expensive equipment like laser tracker and limits essentially working area because of reflector visibility. Another group of the on-line methods is based on information from the internal robot sensors, they can be implemented relatively easily and usually do not impose any restriction to the robot workspace. However, these methods require rather accurate geometric and stiffness models of the

* Corresponding author.

E-mail address: a.klimchik@innopolis.ru (A. Klimchik).

manipulator, which should be obtained from the dedicated experimental study [27–32]. The most essential limitation of the on-line approach is related to necessity of the manipulator model modification in robot controller software, which is usually not completely opened for the end-user. In contrast, the off-line error compensation technique does not require any intervention in the controller software, it is based on the modification of the target trajectory that is obtained using either complete or reduced manipulator models [33–35]. As follows from our experience, even simplified models are able to compensate about 80% of manipulator compliance errors [35–37], while sophisticated complete model is able to compensate about 95% of the end-effector deformations [38,39]. In practice, an appropriate error compensation approach can be selected based on the available equipment and demands of technological process in terms of robot workspace and positioning accuracy.

Another trend to improve manipulator accuracy under the loading is based on mechanical methods, where the manipulator stiffness enhancement is achieved by means of closed loops, which transform conventional serial robots into quasi-serial ones. The most common way here is using gravity compensators [40,41], which in fact do not affect essentially manipulator stiffness but reduce the torque in the actuated joints induced by the external loading. An alternative way is to use kinematic parallelograms [42–44], which potentially improve robot stiffness but should be investigated in more details. Moreover, even brief analyses showed that advantages of manipulators with kinematic parallelograms are not so evident. This poses the problem of comparison study and accuracy analysis of serial vs. quasi-serial manipulators for different applications.

To address the problem, it is required to develop dedicated performance measure that takes into account particularities of manufacturing technologies. In classical robotics, robots are usually compared from point of view of their kinematic properties [45–47], in particular using different norm of the kinematic Jacobian [48,49]. However, these performance measures do not suit well to the manipulator under the external loaded since they are not able to take into account robot elasticity and influence of the external force applied to the manipulator end-effector. To overcome this difficulty, in robotics several other performance measures were developed that are based on the norms of the Cartesian stiffness matrix [50–53] or manipulator deflections at the specific “test pose” [54–56]. Nevertheless, they cannot be applied directly to the robot architecture comparison since they ignore some important technological issues. In industrial practice, to evaluate final product quality there exist several norms estimating the path straightness (ISO 12780), the surface flatness (ISO 12781) and the path roundness (ISO 12181) [57–60]. These performance measures are quite suitable for estimation of the final product quality, but can be hardly applied to manipulators comparison analysis. For this reason, this paper proposes another industry oriented performance measure allowing technological experts to evaluate and to compare robot capabilities using criteria generally accepted in their area.

The remainder of the paper is organized as follows. Section 2 presents particularities of stiffness modeling for serial and quasi-serial manipulators. Section 3 discusses impact of model simplification on the robot comparison. Section 4 deals with comparison of robot performances without consideration of any particular constrains. Section 5 compares architectures of several industrial robots taking into account their particularities. Section 6 provides discussion on some important issues that were outside of the main scope. Finally, Section 7 summarizes main contributions of the paper.

2. Problem of compliance error reduction for serial and quasi-serial manipulators

2.1. Stiffness modeling of industrial robots

Typical serial manipulators (or so-called articulated robot) contain three main components: robot base, robot arm and robot wrist (Fig. 1a). The robot base defines the arm orientation with respect to the robot world frame and as a rule contains a single actuated joint providing rotation around z-axis. As show in Fig. 1a, the link #1 provides shifting of the axis #2 with respect to the axis #1. The robot arm is responsible for the major movements of the robot end-effector. For 6-dof non-redundant robots, the translational movements are usually realized using two actuated joints (the joints #2 and #3). In the anthropomorphic manipulators, these joints are also referred to as robot shoulder and elbow. Corresponding links #2 and #3 define manipulator workspace. The orientation movements are provided by the robot wrist. In the majority of manipulators, the robot wrist contains three revolute actuated joints (joints #4, #5 and #6) whose axes are intersected in the same point (so-called spherical wrist). In relevant geometric model, the linear parameters of the wrist may be omitted and included in the parameters describing the link #3 and the tool transformation. However, in practice, the robot can be equipped with non-spherical wrist (off-set wrist, hollow wrist, etc.) whose geometrical model includes more parameters to be considered.

Quasi-serial robots have roughly similar architecture (see Fig. 1b). In contrast to strictly serial manipulators, the robot arm of the quasi-serial manipulator contains kinematic parallelogram, which can be treated as an internal closed-loop. For this reason, such robots are often called quasi-serial ones. In practice, the kinematic parallelogram allows robot designers to increase robot dynamic properties by means of reduction moving masses (locating heavy actuating motor #3 on the robot base instead of robot elbow). Usually the parallelogram does not affect essentially manipulator control and does not change manipulator direct/inverse kinematic equations. On the other hand, the stiffness model of quasi-serial manipulator essentially differs from it serial counterpart since re-location of the manipulator compliant element (actuator #3 transmission) essentially influence the stiffness behavior [61]. For this reason, previous results obtained for strictly serial manipulators cannot be used here directly.

Stiffness model of robotic manipulator (both serial and quasi-serial) describes the manipulator behavior under the loading (both internal and external) [62–64]. In addition to the conventional robot parameters (geometric ones), it includes a number of elastic parameters describing flexibility of manipulator links and joints. In number of industrial applications, the manipulator elasticity cannot be ignored since the high loading is applied to the robot, while the required positioning accuracy is rather high. These compliance errors can be reduced down to admissible level using both on-line and off-line error compensation techniques that are

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