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Optimal robot positioning using task-dependent and direction-selective performance indexes: General definitions and application to a parallel robot

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A B S T R A C T

Performance evaluation is an important issue for optimal robot positioning within workcells. Performance indexes can provide essential contributions to such an evaluation, in particular if they can account for the specific task with respect to which the optimization is carried out.

This paper introduces a performance index for parallel manipulators called task-dependent performance index (TPI), which explicitly accounts for both robot kinematics and task geometrical features. It is proved that TPI can provide accurate evaluation of robot performances in executing specific tasks. Hence, optimal robot/task relative positioning can be straightforwardly achieved by maximizing the proposed TPI.

The TPI formulation is based on the one of direction-selective performance index (DSI) that is here extended to evaluate parallel manipulator translational capabilities along generic directions. In particular, the TPI definition explicitly accounts for the length and direction of the sequence of translations to be accomplished by a robot to carry out a task.

As a proof of concept, the TPI formulation has been here employed in a maximization algorithm in order to optimize the location of some pick-and-place tasks within the workspace of an industrial 4-RUU parallel robot. The experimental results collected provide adequate evidence of the effectiveness of the proposed index and of its usefulness in optimal robot positioning.

1. Introduction

Robot design optimization plays a crucial role in the ever-continuing effort to improve robot performances and increase their productivity. Several approaches have been proposed to address performance optimization problems, they usually focus on the following issues:

- optimization of the design configuration of a given manipulator [1–5],
- improvement of the workspace reachability in an environment with obstacles or maximization of the workspace volume [6–8],
- optimization of robot architecture by considering several criteria simultaneously [9–12],
- optimization of the scheduling and the robot configuration for some task points in order to minimize the trajectory run time [13,14] and
- optimization of robot positioning (base placement) for prescribed tasks [15].

As far as the first approach is concerned, some researchers have addressed the optimization of the dexterity characteristic of a robot [1–2] or of kinematic isotropy [3–5] in order to obtain an optimal design. A simple index based on the upper bound for a standard condition number of the Jacobian matrix has been proposed in [2] and applied to the kinematic design optimization of a planar redundant manipulator. In [3] a genetic algorithm has instead been developed by exploiting the global isotropy index in order to find optimal link lengths of the best isotropic robot configurations at optimal end-effector working points. Some years later, in [4] another index has been derived from a homogenized isotropy condition of a properly weighted Jacobian matrix. A general criterion for kinematic design optimization has then be developed in order to identify the optimal design configuration of a given manipulator.

As previously mentioned, another chief robot characteristic which can be optimized is workspace. Workspace highly affects the tasks to be performed, especially when the environment is complex, dense or cluttered. In [6] a genetic algorithm has been used to establish the base position and type of a manipulator optimizing workspace reachability in an environment with obstacles. Several years later, a genetic algorithm-based approach has been presented in [7] for workspace optimization of six-dof parallel micro robots. The objective of such a study was to

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evaluate optimal link lengths which maximized the workspace. The effort towards workspace optimization makes sense mainly in parallel robots which usually have a workspace volume smaller than the that of serial robots.

A few works also addressed the optimization problem by considering several criteria simultaneously [9–11]. In [10] an optimal kinematic design method suitable for parallel manipulators has been developed. The solution of such an approach is a design which represents the best compromise between manipulability and a new performance index, named space utilization, whose value reflects the ratio between workspace size and the physical size of the robot structure. Li and Xu in [11] developed a mixed performance index using the space utility ratio for kinematic optimization of manipulators. This index is a weighted sum of global dexterity index and a space utility ratio and it is helpful in optimizing the architecture of parallel manipulators. In [12] a multiobjective optimization procedure has been suggested for neurosurgical serial robots. Such a procedure is addressed at identifying the best robot kinematic structure in terms of workspace, stiffness and invasiveness.

Other works have been focused on the concurrent optimization of robot scheduling and configuration in some industrial operations. In these cases, a primary problem for robotized cell designers is the optimal scheduling of the task point order minimizing the task execution time. This problem is reminiscent of the classic “traveling salesman problem”, but the quantity to be optimized is time instead of distance. A simultaneous research of the optimal scheduling and of the optimal choice of the configurations of the robot for each task point has been presented in [13]. In order to minimize the trajectory run time of the robot the elastic net method has been used which permits to minimize an energy function using a modified gradient method. Because of the considerable computer time cost it is very difficult to use such a method in the case of robots with more than three degrees of freedom. A method based on genetic algorithms has instead been proposed in [14] to determine the minimum cycle time of a manipulator visiting several task points exactly once. Both the task point visit order and the multiple solutions of the inverse kinematic problem are considered. Such an algorithm can be applied to any non-redundant manipulator with up to six-degrees of freedom.

Regarding the determination of the optimum base location of a robotic manipulator, a hybrid heuristic method has been presented in [15]. Such a method combines a genetic algorithm, a quasi-Newton algorithm and a constraints handling method.

This paper focuses on an optimization problem similar to the ones tackled in [15]. In particular, it addresses the issue of seeking the optimal relative position between a robot and a generic task composed of an arbitrary sequence of straight line movements. The optimization problem is translated into the problem of selecting the relative position maximizing a suitably defined performance index, which explicitly accounts for both the robot kinematics and the task geometrical features. The performance index introduced in this work has been specifically developed for parallel robots (as all the indexes discussed in [16]) and represents an evolution and a generalization of the direction-selective performance index (DSI) first presented in [17] and [18]. DSI allows obtaining uncoupled evaluations of the horizontal and vertical translational capabilities of parallel robots along selected directions. So far the DSI definition has been restricted to directions coinciding with the axes of the world reference frame. In this work a more general definition is achieved (i.e. a definition holding for any direction in the Cartesian space) and then employed to develop a task-dependent performance index (TPI), i.e. an index also accounting for the sequence of movements to be accomplished by the robot during the task. TPI is meant to provide evaluations of robot performances in task execution, hence robot optimal positioning can be easily addressed by TPI maximization. The proposed index is fully kinematic, therefore it do not take into account the dynamic behavior of the manipulator. As a consequence, accurate performance evaluations can be achieved only if dynamic loading plays a marginal role, namely when the links and the load of the robot are light and when servomotor dynamics is negligible.

As a proof of concept, the TPI formulation has been here employed in order to optimize the location of some pick-and-place tasks within the workspace of an industrial parallel robot. The industrial parallel manipulator considered is the Adept Quattro™, which belongs to the family of four-leg delta-like (4-RUU) manipulators. Such an high-speed manipulator has a very light mechanical structure thanks to carbon fiber construction and fixed frame-mount of the motors. It is typically employed in the food industry [19] but also in other industrial [20] and research applications [21] where very light objects have to be moved. In these applications, dynamic loading scarcely influence the robot performance, which makes its evaluation through the TPI particularly effective.

In summary, there are four main motivations for this work

- Developing a more general DSI formulation that can be employed to evaluate parallel manipulator translational capabilities along generic directions, not necessary coinciding with the axes of the world reference frame.
- Presenting the Task-dependent Performance Index based on the DSI formulation.
- Introducing a TPI-based method for optimal robot/task relative positioning.
- Proving the practical usefulness of the proposed method by means of experimental tests on a parallel robot.

The paper is organized as follows: in Section 2, the improved DSI formulation suitable for displacements along generic directions is proposed. In Section 3 the proposed Task-dependent Index TPI is explicitly introduced and the optimal location problem is discussed. Then, in Section 4, the TPI definition is applied to the family of 4-RUU parallel manipulators and a numerical investigation is carried out to stress the differences between DSI and TPI performance predictions. Section 5 shows the results of the experimental tests carried out to verify the effectiveness of the proposed indexes DSI and TPI. A through comparison is performed between numerical expectations and experimental measurements. In particular, with reference to the TPI, the time taken to carry out several pick-and-place tasks is compared with the TPI values. The comparisons prove a recurrent satisfactory adherence between the TPI performance variation predictions and the robot actual performances. It is shown that an optimal relative positioning between the robot and the task can be straightforwardly achieved by simply maximizing the TPI. Finally, concluding remarks and future directions are provided in Section 6.

2. Direction selective index (DSI): a general definition

The direction-selective index DSI first introduced in [17] and then extended in [18] allows evaluating independently the translational capabilities, and hence the performances, of a parallel manipulator along the axes of its world reference frame. The basic ideas behind such an initial definition of DSI are reported below for the reader’s convenience. They represent the theoretical background to the more general DSI definition