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Screening of factors influencing the performance of manipulator using combined array design of experiment approach

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ABSTRACT

A robot must manipulate objects with high accuracy and repeatability to perform precise tasks. However, deviation in performance is attributed to uncertainties and improper selection of control, noise, and process factors. The information regarding the effect of these factors on performance is almost non-existent. A probabilistic approach has been used to model and simulate the performance of manipulator. The combined array fractional factorial design of experiment approach has been employed to identify the significant factors and their interactions. This approach helps in screening of the manipulator factors and focus on those that are important. To explore further, two indices, viz. link length ratio and link mass ratio, have been proposed and impact of these indices on manipulator performance is investigated. A two degree of freedom (2-DOF) RR planar manipulator performing a task with cubic and quintic trajectory has been used to illustrate the approach. It has been observed that the statistically significant factors are different for different tasks in workspace. It has also been observed that for the same task, factors responsible for performance variations are different for cubic and quintic trajectories. Finally, it has been demonstrated that the link length ratio change has significant influence on performance compared to link mass ratio.

1. Introduction

Manipulators for many industrial applications are required to perform tasks with higher precision and speed than those of human being. To perform a task, manipulator is commanded to move its end effector (EE) to a desired position, but the actual position reached by EE may be quite different. This difference in the actual and desired position is attributed to inaccuracies present in control, noise in process parameters of manipulator, and improper selection. The attempt to analyze the effect of different parameters on performance of manipulator is very important in the sense that the designer can focus only on parameters that have significant influence on performance variations rather than focusing on several insignificant parameters. Without proper knowledge on the impact of parameter values on the performance, robotic system designer often decides parameter values by intuition, fulfilling some kinematic performance criteria like manipulability index, condition number, etc. Conducting physical experiments on manipulators by changing its parameters is very tedious, time consuming, and uneconomical. Along with this difficulty, the measurements of performances are costly and difficult to measure. To reduce this problem, help of simulation is taken where experiments are conducted by varying values of the identified factors.

In past, many researchers had attempted statistical analysis of robot performance by changing several process parameters. However, use of simulation model and design of experiment (DOE) technique to study influence of design, process, and noise parameters is rare. Colson and Perreira [1] defined the generalized set of performance criteria and presented statistical technique to extract all pertinent information. Benhabib et al. [2] introduced a direct and inverse manipulator error analysis while Azadivar [3] conducted the stochastic analysis of manipulator error. Chen and Chao [4] examined the error sources that contribute to the differences between computed and the actual positions of robots with rotary joints and concluded that details required to model the differences can be reduced significantly after error compensation. Bhatti and Rao [5] introduced the concept of manipulator kinematic reliability, which is a probabilistic measure of manipulator performance.

A few researchers have already addressed optimal robot design problem. For optimal design, Manoochehri and Seireg [6] utilized a dynamic programming approach for form synthesis and control. The optimum parameters were selected in a stagewise manner without sacrificing the interactions inherent in the highly coupled nonlinear systems. Offodile and Uguwu [7] investigated the effect

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of various process variables such as speed of the tool center point and payload on the robot repeatability while Jiang et al. [8] analyzed the operational factors, such as speed and load, to optimize the operational conditions. Wu et al. [9] applied the Taguchi method to determine a robot's accuracy and repeatability. Seven operational factors (load, speed, design, orientation, direction, height, and starting point) were tested using this technique. Kao and Gong [10] investigated issues regarding robotic workspace utilization, accuracy, repeatability, and statistical considerations of fixture design that are relevant to the computer integrated manufacturing system integration. Agarwal and Veeraklaew [11] attempted to design robots using collocation techniques by which parameters can be adjusted to optimal value for a given sequence of motion. Edan et al. [12] developed a three-dimensional statistical evaluation framework for performance measurement of robotic system. Mavroidis et al. [13] presented the design characteristics of the patient-positioning system and described the methodology to perform the error analysis of serial link manipulators. Riemer and Edan [14] observed experimentally that there is statistically significant difference between repeatability at different locations in the workspace and at different height of the target point. Rao and Bhatti [15] proposed probabilistic approach to compute the kinematic and dynamic reliabilities of the manipulator. Szkodny [16] had focused on sensitivities of manipulator positioning to errors of kinematics parameters and highlighted the sensitivity of mass forces to errors of dynamics parameters. Veryha and Kurek [17] developed a method to improve robot EE pose accuracy using joint error mutual compensation and located configuration with highest EE accuracy while Rout and Mittal [18] applied the Taguchi method to detemine the optimal parameter settings of manipulator for improved quality of performance.

In recent times, researchers have attempted to obtain a robust design of products or processes that have minimal performance variations. Otto and Antonsson [19] extended the Taguchi method to make it viable for design problems. Many researchers have criticized the Taguchi method for various drawbacks and Chen et al. [20] proposed an alternative method for robust design and compared their procedure with the Taguchi method. Rout and Mittal [21] extensively reviewed the methodologies available to obtain robust design of products, which have less performance variations that are caused by variations of control factors and noise factors. Subsequently Rout and Mittal [22] determined optimal manipulator parameter tolerance using full factorial DOE approach without considering noise factor array. Meggiolaro et al. [23] proposed error compensation routines for a high-accuracy large medical manipulator and calibrated positioning of EE errors under significant task loads. Alici and Shirinzadeh [24] presented a systematic approach for representing and estimating the Cartesian positioning errors of manipulators with analytical functions such as Fourier polynomials and ordinary polynomials. Kim [25] presented a basic framework of task-based design through a simplified design example, which formulates task specifications, manipulator specifications, and a performance index. Thereafter he obtained the optimized design parameters by a genetic algorithm, which is efficient and effective for nonlinear and complex problems such as task-based design. Subsequently Rout and Mittal [26] proposed search-based method to simulate performance of manipulator and applied DOE technique to identify and determine optimal parameter combinations. However, this approach did not discuss the effect of noise factors, time law of trajectory, and tasks on performance explicitly.

The objective here is to identify the factors that have significant impact on performance variations of the manipulator. It is known that the simulation of real-life performance of a manipulator is quite complex due to the nature of kinematic and dynamic models and it is even more complex to incorporate the effect of noise factors in performance. To avoid these difficulties, a probabilistic approach has been used, which is different from the method discussed in Rout and Mittal [26]. The present paper discusses the effect of noise factor explicitly. These are friction at joints, joint clearances and play, fluctuation in joint torque, and assembly and manufacturing tolerances. A combined array fractional factorial DOE approach is discussed and used to screen the important factors of the manipulator. The impact of tasks and trajectories on performance variations of manipulator is explored. Finally, the effects of link length ratio and link mass ratio change on performance are investigated.

This paper is organized in six sections. In Section 2, steps for application of combined array fractional factorial DOE technique to a two degree of freedom (2-DOF) RR planar manipulator have been discussed. The methodology used to simulate the performance of manipulator is discussed in Section 3 and the simulated performance is analyzed in Section 4 using analysis of variance (ANOVA) technique. To compliment the statistical analysis, the effect of link length ratio and link mass ratio change on performance is investigated in Section 5. The paper is concluded in Section 6.

2. Application of fractional factorial DOE technique to a 2-DOF RR planar manipulator for parameter screening

Fractional factorial DOE technique has been applied satisfactorily in several engineering applications. However, application of this technique to manipulator design problem has not been attempted so far. To investigate the effect of parameters on performance of manipulator, a 2-DOF RR planar manipulator is considered. The steps for fractional factorial DOE technique are discussed below.

The experiments to screen the factors are usually performed at the early stages of a design project when it is likely that many of the factors initially considered have very little or no effect on the performance. For the conduct of experiment, the control factors and noise factors [26] are identified. Effects of these factors are investigated using different level values. As the number of levels increases for each control and noise factor, the number of combinations becomes large and unmanageable. Therefore, running experiments with all the combinations becomes uneconomical and time consuming. As industrial manipulators have many control and noise factors, the factor combinations are generated using "fractional factorial DOE approach" and the factors responsible for performance variations are identified using this approach.

The steps utilized to conduct and analyze the experiments are available in [27]. The methodology for fractional factorial DOE approach is similar to those described for full factorial DOE approach in [26]. The steps other than those discussed in [26] are given below.

2.1. Statement of the problem

It is desired that the manipulator must reach the commanded destination in the workspace accurately following a particular trajectory. For a 2-DOF RR planar manipulator, the task is always specified by the start and destination point in the workspace. The start point is denoted by $P(x_i, y_i)$ and the destination point by $P(x_f, y_f)$, where workspace is xy-plane. The kinematic and dynamic models of the manipulator are used to simulate the performance at the destination point when it follows a particular trajectory.