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Fundamental framework toward optimal design of product platform for industrial three-axis linear-type robots

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Abstract

This paper discusses an optimization-based approach for the design of a product platform for industrial three-axis linear-type robots, which are widely used for handling objects in manufacturing lines. Since the operational specifications of these robots, such as operation speed, working distance and orientation, weight and shape of loads, etc., will vary for different applications, robotic system vendors must provide various types of robots efficiently and effectively to meet a range of market needs. A promising step toward this goal is the concept of a product platform, in which several key elements are commonly used across a series of products, which can then be customized for individual requirements. However the design of a product platform is more complicated than that of each product, due to the need to optimize the design across many products. This paper proposes an optimization-based fundamental framework toward the design of a product platform for industrial three-axis linear-type robots; this framework allows the solution of a complicated design problem and builds an optimal design method of fundamental features of robot frames that are commonly used for a wide range of robots. In this formulation, some key performance metrics of the robot are estimated by a reduced-order model which is configured with beam theory. A multi-objective optimization problem is formulated to represent the trade-offs among key design parameters using a weighted-sum form for a single product. This formulation is integrated into a mini–max type optimization problem across a series of robots as an optimal design formulation for the product platform. Some case studies of optimal platform design for industrial three-axis linear-type robots are presented to demonstrate the applications of a genetic algorithm to such mathematical models.

Keywords: Product family; Product platform; Optimal design; Reduced-order model; Multi-objective optimization; Industrial robot

1. Introduction

Three-axis linear-type robots are a type of industrial robot commonly used in manufacturing assembly lines. There are many types of such robots designed to operate over a range of speeds, distances, and orientations, working with objects of different weights and shapes. While these robots may differ in their specifications, they share many common attributes of their basic operation, and have many structural similarities. If common parts or modules can be used across a wide range of robotic systems, more efficient machine design and production can be expected [1]. Therefore, many such robots are produced in series and have been developed with share structural designs. Since it is necessary to consider many factors simultaneously to achieve the integrated design of a product family, such design is presently performed empirically. However, the resulting designs may not be optimal. Therefore, the method to design optimal platform is required for overcoming the issue.

The research described in this paper proposes an optimized method to design a platform for a series of industrial three-axis linear-type robots. First, a reduced-order model based on beam theory is introduced to comprehensively represent key robot functions and performance. A multi-objective optimization problem focused on a single product is formulated with the model. This research assumes that the cross-sectional shape of the robot frame plays a key role in the design of the robot platform. The single product design thus formulated is then expanded to the problem of designing optimal product

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platforms which are commonly used across a series of robots. Several case studies of optimal platform design of industrial three-axis linear-type robots are presented, using a genetic algorithm applied to the reduced order mathematical model. Finally, this paper concludes with a verification of the proposed framework and a discussion of applications of the model to actual engineering situations.

2. Integrated design of industrial three-axis linear-type robots

2.1. Robot design issues

Several types of three-axis linear-type robots have been developed to satisfy market demands. Although their function and performance are different, they have a common basic structure and employ similar motions. In order to save effort for designing and to reduce manufacturing costs, parts with similarities across machine types have been gradually commonalized. This effort at commonalization has sometimes been performed for each type or series on a day-to-day basis, and the resulting designs may not be optimal if the whole product family is considered. Designing the product variants in an integrated manner, not individually, from the initial design stage is an effective way to optimize the process.

2.2. Integrated design for industrial three-axis linear-type robots

This subsection discusses possible approaches to achieve common designs for three-axis linear-type robots. Since such robots consist of several frames, we first consider the cross-sectional shapes of these frames as a potential common product platform. If the cross-sectional shapes of the frames are commonalized, the parts which are attached to the frames can likewise be commonalized, resulting in a reduced number of dies required to produce these parts and reduced production costs. However, if these attempts at commonalization go too far, the robots cannot meet customer requirements, due to lack of frame rigidity, excess machine weight, and so on. On the other hand, if a variety of cross-sectional shapes are produced, the customer requirements may be met flexibly, but at a cost of increased lead times and design and manufacturing costs. This inevitable trade-off between such costs and customer satisfaction makes it necessary not to share the cross-sectional shape haphazardly but to deploy it within a product family considering the optimal degree of design commonality. To achieve this, it is important to optimally design the varieties and shapes of the cross sections.

Customers commonly require that robotic arm motion speed and positioning accuracy be maximized, while minimizing robot size and weight. Optimally designing the product platform considering all of those requirements is necessary to improve customer satisfaction. Therefore, the design problem of an individual robot becomes a multi-objective optimization problem, requiring a new optimization method.

2.3. Mathematical method for integrated design of a product family

Manufacturers have attempted to design product variants which share a common concept, while maintaining high quality design of individual products. Recently, the range of application of such integrated design has been extended to various products [2]. The movement in industry has prompted research into the theory and methodology of integrated design of product variants, known as "product family design" [1] or "integrated product family design" [3]. Integrated design of a product family is more complicated than the design of individual products, because it must address more factors which affect the quality of the design solution. Therefore, an optimization-based approach with mathematical formulation of relationships among those factors is recognized as an effective way to achieve excellent design solutions across an entire product family [4]. Optimization of product family design requires mathematical definition of some design operations, e.g., commonalization of certain parts among different products, sharing such parts among different manufacturers, and modularization of certain parts of a product by separating them from the other parts. The approach also uses mathematical definitions of evaluation indexes; these may include an overhead cost reduction index (describing development or equipment costs that are reduced by commonalization) and a flexibility index (quantifying the improvement in product deployment by modularization). In addition, a suitable optimization algorithm for the above formulation must be used.

2.4. Research approaches

This paper explores the optimal design of a product platform for an integrated product family design for three-axis linear-type robots, taking the following three approaches:

(1) Introducing a reduced-order model suitable for the design problem.
(2) Defining the performance evaluation index which has to be understood before the details of the robots are fixed.
(3) Formulating the design problem and building the method of solving the problem.

Approach (1) corresponds to a recent research topic in design engineering called 1DCAE [5], which has been recognized as a potential approach for model-based design in the early stages of product development. Here, "1D" does not mean one-dimensional, but rather more like "first order": describing the essence of the problem and representing product performance in a simple but comprehensive form. The 1DCAE approach attempts total optimization of product design with simulations based on physical models. This research introduces a physical model which simplifies the form of the three-axis linear-type robot. Approach (2) addresses the difficulty of considering all customer requirements of the robot in the early stages of design. Key performance evaluation indexes and