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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 commonalized parts are determined by analyzing the customer requirements and the robot structure. In approach (3), the optimal design methods proposed in the previous research are applied to this case, in which the design problem of an individual product is formulated as a multi-objective optimization problem, based on the results of the approach (2).

3. Product platform and individual design problem

3.1. Common parts of industrial three-axis linear-type robots

An example of the three-axis linear-type robot which this research focuses on is shown in the left side of Fig. 1. Its maximum payload, slide stroke of each arm, and positioning accuracy must match operational requirements. Furthermore, customers usually have their own requirements for robot performance, such as maximum arm speed, high positioning accuracy, and minimal weight. The motors and the frames of the robots strongly affect these performance metrics. Therefore, the robot motors and frames should not be commonalized; instead, a variety of options should be available. Other machine components do not have such a great influence on system performance, such as the junction parts between frames. Since these parts are moving parts or couple to moving parts, they tend to require regular maintenance, and directly affect the amount of required replacement parts that must be stocked. Therefore, such components should be commonalized for a wide range of robot designs. If the cross-sectional shapes of frames are commonalized, the injection parts can also be commonalized, since they slide on the frames. Consequently, the cross-sectional shapes of frames are designated as the product platform for the robots and the product family is deployed by designing the frame length according to the customer requirements.

3.2. Fundamental constitution of reduced-order model

Roughly speaking, the requirements for three-axis linear-type robots are maximizing their basic performance metrics, i.e., their speed and accuracy, and minimizing costs, which are determined by the weight and the size of the robots. In regards to accuracy, emphasis is placed on the displacements of the vertical frame head at the object catch point and release point. These performance metrics cannot be grasped concretely in the stage that the cross-sectional shapes of the frames are determined in the condition that detail of the individual robot has not been fixed yet. Then, assuming that the robots' structure can be represented by a combination of frames, this research approximates those frames by beams. As shown in the right side of Fig. 1, the performance evaluation index of the motion accuracy is defined by replacing those frames with beams and calculating displacements of the top of the vertical frame at the motion start and end points. The other performance evaluation indexes concerning the weight and size of the robots and the arm speed can be roughly evaluated by the weight of the robots. Therefore, the total robot weight, estimated by the approximation model, is also designated as a performance evaluation index. Under the above approach, the reduced-order physical model of the robot in Fig. 1 is constructed with the following assumptions:

- Each frame is a solid with rectangular cross-sectional shape. The empty weight of frames is modeled as a uniformly distributed load.
- The cross-sectional shape of the traverse frame has the fixed aspect ratio of height to width = 3:2; that of the vertical frame has a free aspect ratio; and that of the kick frame is a square.
- The weight of the frames and the junction parts including motors are modeled as a uniformly distributed load on the frame which supports them.
- The motors are chosen from a predesigned set, that is, the weight of a motor is discrete. However, the weights are calculated with a continuous relationship between the weight of frame and that of motors.
- The behavior of each frame is estimated by the beam theory.
- Since torsional deflection in the traverse frame has a greater influence on the whole robot than that in other frames, torsional deflections are not considered except for that in the traverse frame.
- The frames do not lean due to backlash in the junction parts.

3.3. Optimal design model of the individual product

Under the assumptions introduced in the previous section, the optimal design model of an individual product may be determined as shown below. The design variables are carefully

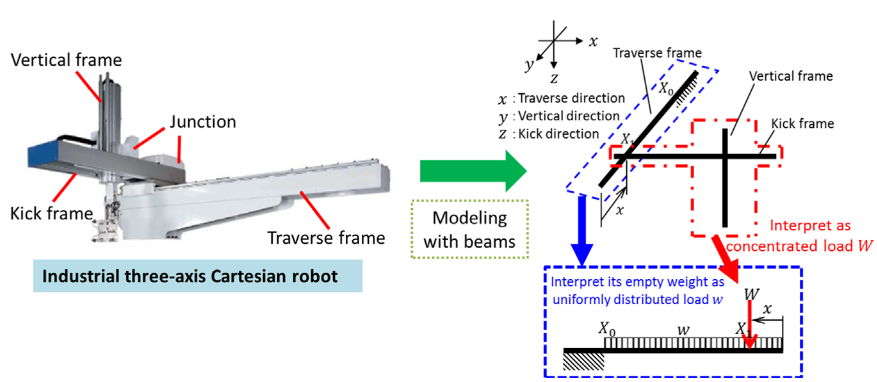

Fig. 1. Configuration of a three-axis linear-type robot and its modeling.

selected: the height of the cross-section of the traverse frame h_1, that of the vertical frame h_2, that of the kick frame h_3, and the width of the cross-section of the vertical frame b_2. The required specification is determined as the weight of the handled object m_p [kg], and the length of each frame L_1, L_2, L_3. To minimize the displacement of the vertical frame head at the object catch point d_c, the displacement at the object release point d_r, and the weight of the robot M are determined as objective functions. The conditions regarding robot shape and strength are considered as constraints. Consequently, the design problem is formulated as the multi-objective optimization problem shown below

$$\left.\begin{array}{ll} \text{Find} & h_1, h_2, h_3, b_2 \\ \text{Minimize} & M, d_c, d_r \\ \text{Subject to} & 100 \le h_1 \le 350 \quad 100 \le h_2 \le 300 \\ & 50 \le h_3 \le 300 \quad 50 \le b_2 \le 300 \\ & \sigma_3 \le \sigma_a \\ \text{For given} & m_p, L_1, L_2, L_3, \sigma_a \end{array}\right\} \quad (1)$$

In the above expression σ_3 is the maximum stress that is generated in the vertical frame when the robot picks up an object, and σ_a is the allowable stress of the vertical frame. The upper limits and lower limits of h_1, h_2, h_3, b_2 are defined by the analysis of the data of actual robots. Since the displacements are considered in the objective functions, the internal stress in the traverse and vertical frames need not be included in the expression explicitly.

4. Optimal design of product platform and calculation method

4.1. Optimal design for individual requirement specification

Before the product family design problem is considered, it is necessary to analyze the mathematical structure of product platform optimization for determining common parts and specific product platform deployment. Firstly, the optimal design problem for designing a product P_i for a certain requirement specification p_i can be expressed as shown below [6,7]

$$\left.\begin{array}{ll} \text{Find} & \boldsymbol{x_i} \\ \text{Minimize} & \boldsymbol{f} = (f_1(\boldsymbol{x_i}, \boldsymbol{p_i}), \ldots, f_m(\boldsymbol{x_i}, \boldsymbol{p_i})) \\ \text{Subject to} & \boldsymbol{x_i} \in Feasible(\boldsymbol{p_i}) \\ \text{For given} & \boldsymbol{p_i} \end{array}\right\} \quad (2)$$

where $\boldsymbol{x_i}$ $(i = 1, 2, \ldots, n)$ are design variables which express contents of the product P_i, and $f_j(\boldsymbol{x_i}, \boldsymbol{p_i})$ $(j = 1, 2, \ldots, m)$ are objective functions which evaluate product performances using indices that are to be minimized. The set $Feasible(\boldsymbol{p_i})$ is the feasible region which is limited by $\boldsymbol{p_i}$.

There are various optimization methods for multi-objective optimization problems. However, in this study, the multi-objective optimization problem represented by Eq. (2) is eventuated in the single-objective optimization problem by focusing on one of the objective functions $f_k(\boldsymbol{x_i}, \boldsymbol{p_i})$ and converting other objective functions $f_l(\boldsymbol{x_i}, \boldsymbol{p_i})$ $(l = 1, 2, \ldots, m,\ l \ne k)$ into constraint conditions $f_l(\boldsymbol{x_i}, \boldsymbol{p_i}) \le \varepsilon_l$. Thus, the single-objective optimization problem shown below is derived

$$\left.\begin{array}{lll} \text{Find} & \boldsymbol{x_i} & \\ \text{Minimize} & f_k(\boldsymbol{x_i}, \boldsymbol{p_i}) & \\ \text{Subject to} & \boldsymbol{x_i} \in Feasible(\boldsymbol{p_i}) & \\ & f_l(\boldsymbol{x_i}, \boldsymbol{p_i}) \le \varepsilon_l & (l = 1, 2, \ldots, m,\ l \ne k) \\ \text{For given} & \boldsymbol{p_i}, \varepsilon_l & \end{array}\right\} \quad (3)$$

In this case, $\boldsymbol{\varepsilon_l}$ is defined as $\boldsymbol{\varepsilon_l} = (\boldsymbol{\varepsilon}_1, \ldots, \boldsymbol{\varepsilon}_{\boldsymbol{k}-1}, \boldsymbol{\varepsilon}_{\boldsymbol{k}+1}, \boldsymbol{\varepsilon_m})^{\boldsymbol{T}}$.

4.2. Formulation of the product family design problem for a single common part

Let the partial vector $\boldsymbol{x^c}$ of $\boldsymbol{x_i}$, which represents the common parts, be a given and the other partial vector $\boldsymbol{x^s}$, which represents individual parts, be parameters that can be adjusted optimally when a product is designed to satisfy a certain requirement specification $\boldsymbol{p}$. In this case, the design problem is formulated based on Eq. (3) as

$$\left.\begin{array}{lll} \text{Find} & \boldsymbol{x^s} & \\ \text{Minimize} & f_k(\boldsymbol{x^s}, \boldsymbol{x^c}, \boldsymbol{p}) & \\ \text{Subject to} & (\boldsymbol{x^s}, \boldsymbol{x^c}) \in Feasible(\boldsymbol{p}) & \\ & f_l(\boldsymbol{x^s}, \boldsymbol{x^c}, \boldsymbol{p}) \le \varepsilon_l & (l = 1, 2, \ldots, m,\ l \ne k) \\ \text{For given} & \boldsymbol{p}, \boldsymbol{x^c}, \varepsilon_l & \end{array}\right\} \quad (4)$$

On the other hand, assuming that individual parts $\boldsymbol{x^s}$ can be optimally adjusted based on Eq. (4), the design problem for common parts to fulfill a certain requirement specification p is formulated as

$$\left.\begin{array}{ll} \text{Find} & \boldsymbol{x^c} \\ \text{Minimize} & \min\limits_{\boldsymbol{x^s}} \tilde{f}_k(\boldsymbol{x^s}, \boldsymbol{x^c}, \boldsymbol{p}) \\ \text{For given} & \boldsymbol{p} \end{array}\right\} \quad (5)$$

In this case, the objective function $\min\limits_{\boldsymbol{x^s}} \tilde{f}_k(\boldsymbol{x^s}, \boldsymbol{x^c}, \boldsymbol{p})$ expresses the optimal value found by Eq. (4), when Eq. (4) is applicable.

Based on the above formulation, the design problem for the specific common parts which meets the range of requirement specifications $\boldsymbol{p} \in \boldsymbol{R}$ is formulated as follows:

$$\left.\begin{array}{ll} \text{Find} & \boldsymbol{x^c} \\ \text{Minimize} & \max\limits_{\boldsymbol{p} \in R} \left[\min\limits_{\boldsymbol{x^s}} \tilde{f}_k(\boldsymbol{x^s}, \boldsymbol{x^c}, \boldsymbol{p}) \right] \\ \text{For given} & R \end{array}\right\} \quad (6)$$

4.3. Formulation of the product family design problem with multiple common parts

Finally, this subsection generalizes the previous subsection's situation that the specific common parts $\boldsymbol{x^c}$ are shared among all product variants, to the situation that there are J kinds of common parts $\boldsymbol{x_j^c} (j = 1, \ldots, J)$. This can be formulated as the following optimization problem by expanding Eq. (6)

$$\left.\begin{array}{ll} \textit{Find} & \left[\boldsymbol{x}_1^{c\boldsymbol{T}}, \boldsymbol{x}_2^{c\boldsymbol{T}}, \ldots, \boldsymbol{x}_J^{c\boldsymbol{T}}\right]^{\boldsymbol{T}} \\ \textit{Minimize} & \max\limits_{\boldsymbol{p} \in R}\left[\min\limits_{j=1,2,\ldots,J}\left\{\min\limits_{\boldsymbol{x}^s} \tilde{f}_k(\boldsymbol{x}^s, \boldsymbol{x}_j^c, \boldsymbol{p})\right\}\right] \\ \textit{For given} & R \end{array}\right\} \quad (7)$$

The objective function of Eq. (7) means that this optimization problem focuses on the product variant of best-performance which can be found by the optimal design of all platforms for satisfying a certain requirement specification $\boldsymbol{p}$. In this case, such product variants are found for every point within the range of requirement specification R, and the product variant with worst performance among them is made the best.

5. Formulation for the optimal design of a product platform toward product family deployment

This section introduces the efficient formulation for the product family design problem.

5.1. Adjustment of optimal design model of individual product toward product platform design

Firstly, Eq. (1) is rewritten as the single objective optimization problem in the form of Eq. (3). The objective function in Eq. (1) minimizes the displacements of the vertical frame head at the object catch point d_c and at the object release point d_r; the weight of robot M is also minimized. Assuming that multiple platforms are provided, it is desirable that the lighter the handled load, the lower the robot rigidity, that is, the smaller M. However, too much weight reduction reduces the rigidity and makes d_c and d_r larger. Therefore, considering multiple product platforms and relationships among d_c, d_r, and M of the product variants under each product platform that satisfy the load requirement m_p, we can expect the approximate optimality relationships among the three objectives, M, d_c and d_r over a set of platforms as shown in Fig. 2. Therefore, it is expected that M is minimized and d_c and d_r made uniform to a certain degree for all product variants by placing an upper limit on d_c and d_r.

From the above discussion, the problem is formulated as a single objective optimization by placing the upper limit on d_c and d_r as constraints and narrowing down the objective functions into only the minimization of M. That is, the single objective optimization problem can be formed from Eq. (1), provided that d_c^* and d_r^* are the upper limits of d_c and d_r respectively

$$\left.\begin{array}{lll} \text{Find} & h_1, h_2, h_3, b_2 & \\ \text{Minimize} & M & \\ \text{Subject to} & d_c \le d_c^* & d_r \le d_r^* \\ & 100 \le h_1 \le 350 & 100 \le h_2 \le 300 \\ & 50 \le h_3 \le 300 & 50 \le b_2 \le 300 \\ & \sigma_3 \le \sigma_a & \\ \text{For given} & m_p, L_1, L_2, L_3, \sigma_a, d_c^*, d_r^* & \end{array}\right\} \quad (8)$$

5.2. Optimal design model for a single product platform

Next, the design problem of a single product platform satisfying the full range of requirement specifications R is formulated. In this case, the cross-sectional shapes of three frames (traverse frame, kick frame, vertical frame) of three-axis linear-type robots are treated as a commonalized set, which is designed to satisfy the required load weight. Therefore, there are no individually adjustable parts in this design problem. Design variables include only the common dimension parameters of the cross-sectional shape of each frame, i.e., h_1^c, h_2^c, h_3^c, b_2^c, which are designed for the full range of R. In addition, the optimization of the cross-sectional shapes, which satisfies all points within R with a single platform, should consider the required maximum weight of a load to be handled and the length of each frame. That is, when the maximum value of load weight for R is denoted by m_{max}, and the length of each frame is denoted by L_{max1}, L_{max2}, L_{max3}, the values of h_1^c, h_2^c, h_3^c, b_2^c for $m_p = m_{max}$, $L_1 = L_{max1}$, $L_2 = L_{max2}$, and $L_3 = L_{max3}$ should be found in this design problem. It is trivial that M will have the maximum value M_{max} in the case of $L_1 = L_{max1}$, $L_2 = L_{max2}$, $L_3 = L_{max3}$. Therefore, the minimization of M that has the maximum weight among all product variants produced from a commonalized cross-sectional shape means the minimization of M_{max}. It is also trivial that d_c, d_r will be maximized in the case of $L_1 = L_{max1}$, $L_2 = L_{max2}$, $L_3 = L_{max3}$. Therefore, if those maximum values are defined as $d_{c\ max}$, $d_{r\ max}$, all product variants produced from this single product platform will satisfy the upper constraints of $d_{c\ max}$, $d_{r\ max}$. As a result, the problem for designing the single common parts h_1^c, h_2^c, h_3^c, b_2^c is formulated as

$$\left.\begin{array}{lll} \text{Find} & h_1^c, h_2^c, h_3^c, b_2^c & \\ \text{Minimize} & M_{max} & \\ \text{Subject to} & d_{cmax} \le d_c^* & d_{rmax} \le d_r^* \\ & 100 \le h_1^c \le 350 & 100 \le h_2^c \le 300 \\ & 50 \le h_3^c \le 300 & 50 \le b_2^c \le 300 \\ & \sigma_3 \le \sigma_a & \\ \text{For given} & m_{max}, L_{max1}, L_{max2}, L_{max3}, \sigma_a, d_c^*, d_r^* & \end{array}\right\} \quad (9)$$

5.3. Optimal design model for multiple product platforms

Next we consider the case in which the entire range of requirement specifications R are satisfied with J kinds of product platforms. In this case, J kinds of common parts h_{1j}^c, h_{2j}^c, h_{3j}^c, b_{2j}^c are designed. Since three-axis linear-type robots are classified according to their maximum payload, it is necessary to determine the maximum payload that satisfies the whole requirement specification of the weight of handled loads, that is, to determine the maximum weight that can be carried by each platform.

Therefore, the maximum payload of each platform m_{maxj}^c is added to the design variables and m_{max1}^c is fixed on the maximum weight of handled loads. It is then assumed that the maximum payload of each of the other platforms m_{maxj}^c is

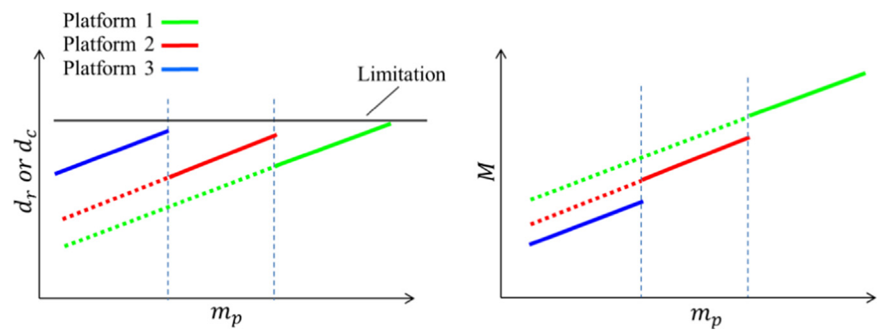

Fig. 2. Optimality relationship among three objectives, M, d_c and d_r over a set of platforms.

within the range of $m_{min} \le m^c_{maxj} \le m^c_{max1}$. Under those constraints, the weights of robots that are produced from each product platform are compared, and M_{maxJ} of a certain platform that has the largest M_{maxJ} is minimized. From the above, the problem of designing J kinds of product platforms is formulated as shown below, provided that h^c_{1j}, h^c_{2j}, h^c_{3j}, b^c_{2j} satisfy the constraints in Eq. (9). In the following, L_{max1j}, L_{max2j} and L_{max3j} are the maximum frame lengths of each platform

$$\left.\begin{array}{ll} \text{Find} & h^c_{11}, h^c_{21}, h^c_{31}, b^c_{21}, \ldots, h^c_{1J}, h^c_{2J}, h^c_{3J}, b^c_{2J}, m^c_{max2}, \ldots, m^c_{maxJ} \\ \text{Minimize} & \max\limits_{j=1,2,\ldots,J} M_{\max J} \\ \text{Subject to} & m_{min} \le \left(m^c_{max2}, \ldots, m^c_{maxJ}\right) \le m_{max1} \\ \text{For given} & m_{min}, m^c_{max1}, L_{max11}, L_{max21}, L_{max31}, \ldots, L_{max1J}, L_{max2J}, L_{max3J} \end{array}\right\} \tag{10}$$

6. Numerical computation example

6.1. Design conditions and optimization algorithm

It is necessary to define the number of platforms, the optimal design model introduced in the previous section, and three performance evaluation indices that are preconditions of that model for product platform design. This research considers three cases, each of which assumes that the number of product platforms $J = 1, 2, 3$ as numerical computation examples. Each case is optimized by the method introduced above.

The calculation conditions are given as $m_{min} = 5$ [kg], $m^c_{max1} = 25$ [kg], $d^*_c = 3$ [mm], $d^*_r = 2$ [mm], and $\sigma_a = 215$ [N/mm]. The maximum values of frame length for each platform are defined as shown below by analysis of performance data of actual robots. In the following, m^c_{maxj} is the maximum payload

$$L_{max1j} = 0.2491\left(m^c_{maxj}\right)^3 - 15.43\left(m^c_{maxj}\right)^2 + 666.5m^c_{maxj} \tag{11}$$

$$L_{max2j} = 36m^c_{maxj} + 1215 \tag{12}$$

$$L_{max3j} = 503.3\left(m^c_{maxj}\right)^{0.4159} \tag{13}$$

In this research, since the formulation includes the mini–max problem, the optimization is calculated by the genetic algorithm on the general purpose optimal design support tool “OPTIMUS Ver.10.9[1] [8]”.

6.2. Results of optimization calculation

The results of optimization of product platforms are shown in Figs. 3, 4 and 5. Fig. 3 shows the weight of robots M in a vertical axis for two requirement specifications in horizontal axes, i.e., the weight of handled objects m_p and the total value L among the length of each frames L_1, L_2, L_3. Fig. 3(a) shows the case of a single product platform, and Fig. 3(b) shows that of two product platforms. Fig. 3(b) shows that Platform 2 covers the area where handled objects are light, although Platform 1 covers the whole area as shown in Fig. 3(a). Fig. 3(c) shows the case of three platforms. Platform 3 covers the area where handling objects are lighter. Similarly, Fig. 4 shows the displacement of vertical flame head at the object catch point d_c, and Fig. 5 shows that at the object release point $d_r$of each case $J = 1$, 2, 3.

6.3. Discussion

As shown in Table 1, a single platform having a maximum payload m_{max} of 25 [kg] covers the whole requirement specification for the case in which products are deployed with a single platform. However, Platform 2 with a maximum payload m_{max} of 8.84 [kg] covers the area in which handled loads are lighter in the case that the number of platforms increases to two. The rigidity of Platform 2 is smaller than that of Platform 1. Moreover, the whole requirement specification is covered by three platforms for which the maximum payloads are 25 [kg], 14.9 [kg], and 5 [kg], when the number of platforms increases to three. Comparing the displacement of the vertical frame head between the case of two platforms and the case of three platforms, their variations are smaller and performance accuracies are more uniform in the latter case.

As shown in Figs. 3–5, the case of a single platform causes overdesign, that is, the rigidity is higher and the robot weight is heavier than necessary in the range of lighter loads, since the cross-sectional shape that can accommodate heavy objects also covers light objects. Such overdesign can be substantially eliminated through uniformization of d_c, d_r by increasing the

[1]OPTIMUS is a trade mark of Noesis Solutions.

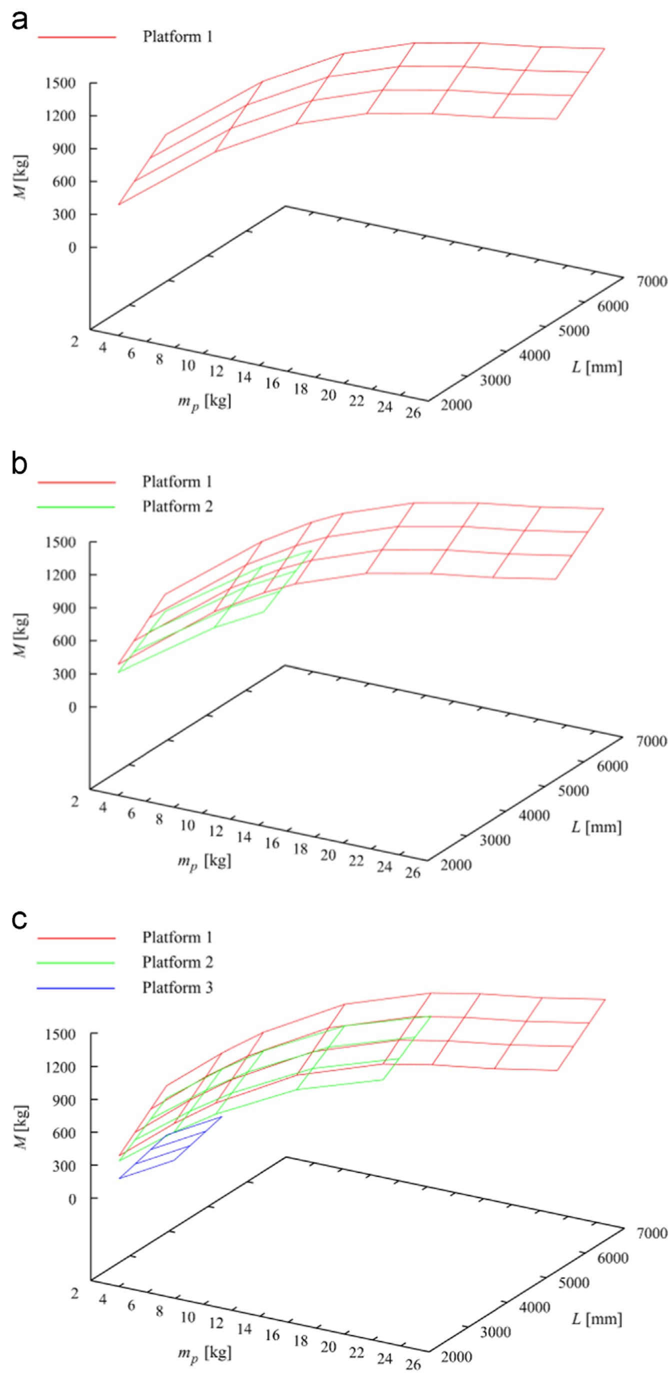

Fig. 3. Influence of the number of platforms on robot weight. (a) Case of a single platform, $J=1$, (b) case of two platforms, $J=2$ and (c) case of three platforms, $J=3$.

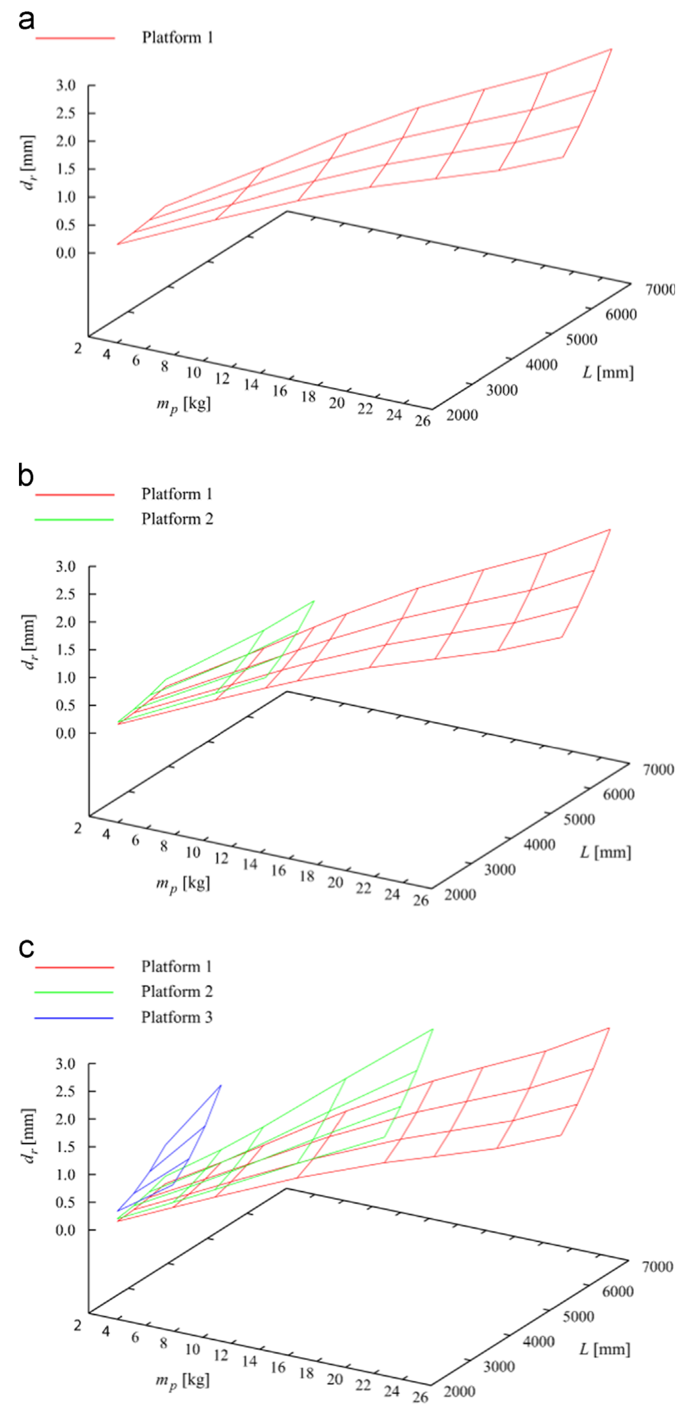

Fig. 4. Influence of the number of platforms on the displacement of vertical frame head at the object release point. (a) Case of a single platform, $J=1$, (b) case of two platforms, $J=2$ and (c) case of three platforms, $J=3$.

number of the cross-sectional shapes as expected from Section 5. Thus, it is appropriate to define d_c, d_r as constraints, which were originally considered as objective functions.

7. Conclusion

This research proposed an optimization method for product platform design in support of an integrated approach to product family design, and built a reduced-order model and calculation method for the optimization. A design formulation framework was demonstrated, in which a design problem of an individual product can be formulated as a multi-objective optimization problem. This formulation framework was applied to the integrated product family design of three-axis linear-type robots using a reduced-order model. The framework was used to derive a formulation that efficiently calculated the actual platform design problem. Finally, the appropriateness and effectiveness of the proposed framework

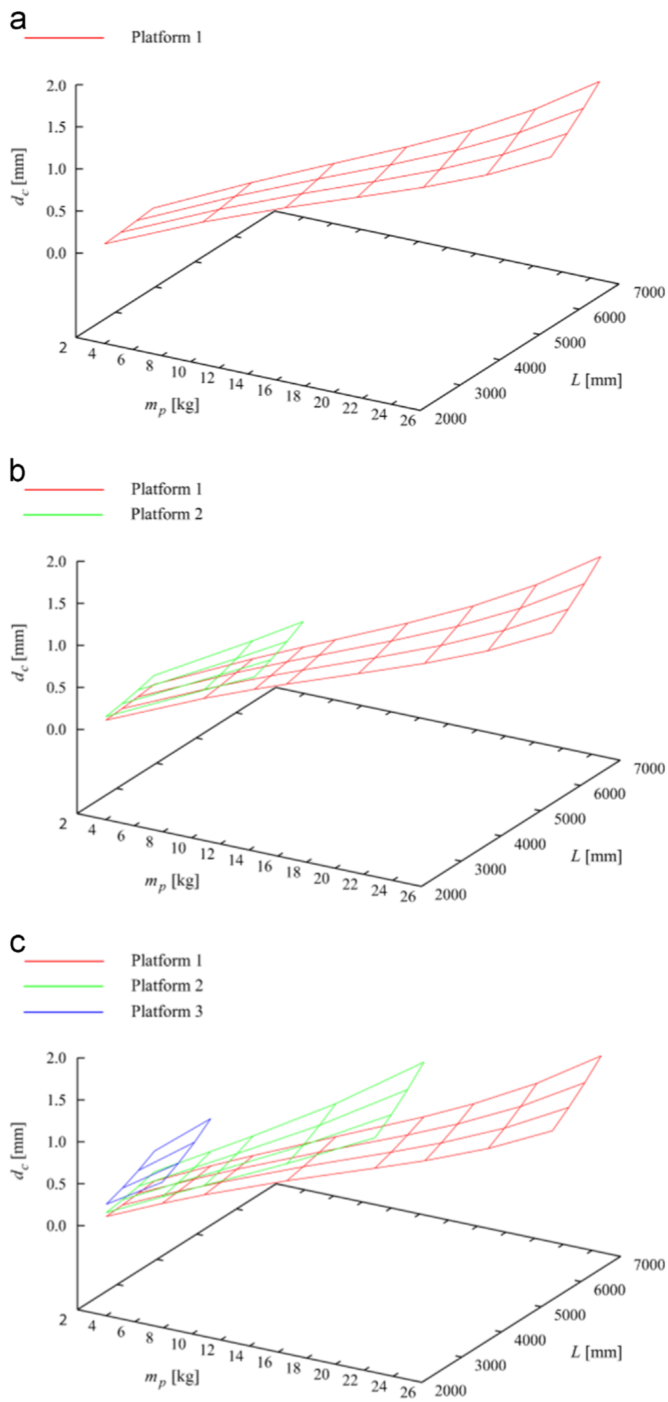

Fig. 5. Influence of the number of platforms on the displacement of vertical frame head at the object catch point.(a) Case of a single platform, $J=1$, (b) case of two platforms, $J=2$ and (c) case of three platforms, $J=3$.

and the formulations based on it were verified by three example cases, which addressed one, two, and three product platforms respectively. Although proposed framework was applied to the three-axis linear-type robots in this paper, other products have similar issues in product platform design. Therefore, proposed framework is expected to apply to other cases in the current industry fields.

Table 1
Comparison of three cases by the contents of optimally designed platforms.

Number of platforms				1	2	3
Design variables	Platform 1	h_1	[mm]	276	275	275
		h_2	[mm]	184	182	184
		h_3	[mm]	51.9	50.0	50.0
		b_2	[mm]	50.2	50.0	50.0
		m_{max}	[kg]	25.0	25.0	25.0
	Platform 2	h_1	[mm]	–	241	248
		h_2	[mm]	–	130	169
		h_3	[mm]	–	50.0	89.2
		b_2	[mm]	–	61.9	50.0
		m_{max}	[kg]	–	8.84	14.9
	Platform 3	h_1	[mm]	–	–	159
		h_2	[mm]	–	–	104
		h_3	[mm]	–	–	56.4
		b_2	[mm]	–	–	50.0
		m_{max}	[kg]	–	–	5.00
Objective functions	Platform 1	M_{max}	[kg]	1342	1329	1334
		$d_{r\ max}$	[mm]	2.70	2.72	2.68
		$d_{c\ max}$	[mm]	1.41	1.43	1.39
	Platform 2	M_{max}	[kg]	–	1088	1088
		$d_{r\ max}$	[mm]	–	1.30	2.49
		$d_{c\ max}$	[mm]	–	0.564	0.998
	Platform 3	M_{max}	[kg]	–	–	313.7
		$d_{r\ max}$	[mm]	–	–	1.76
		$d_{c\ max}$	[mm]	–	–	0.704

Our planned future work includes review and refinement of the reduced-order model. One effort will be to correct the model using data obtained from actual robots in order to reduce gaps between the model and actual robot performance. A second planned effort will be the definition of more suitable evaluation indices based on analysis of customer requirements. It may become necessary to refine the fundamental framework, the formulation method, and the calculation method for the framework toward the optimal product platform design through case studies.

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