A UNIVERSAL DESIGN METHOD FOR REFLECTING PHYSICAL CHARACTERISTICS OF DIVERSE USERS: A CASE OF A BICYCLE FRAME

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ABSTRACT: Research into universal design is necessitated by the adaptation to a worldwide aging society and need for companies to develop internationalization strategies. However, a general design approach for accommodating diverse users' needs has still not emerged. The issue of how to address the physical characteristics of diverse users and needs in a design process is critical. In this study, a set-based universal design was proposed to obtain diverse design solution sets for users with diverse requirements. Both product attribute information such as the dimension of products and the physical characteristics of diverse users as design variables were defined. Furthermore, these design variables were defined as ranged values to accommodate diverse users. As a case study, the proposed method to the design problem of a bicycle frame was applied. This case study defined the height of users, each dimension of bicycle frames, and range of knee joint motion as design variables and constraint condition respectively. By applying the proposed universal design method, diverse bicycle frames including four different types of bicycle frames beyond conventional bicycle frame that satisfy all users were obtained. The suitability of the proposed design method for obtaining diverse ranged design solution sets that accommodate the variability in physical characteristics of diverse users was also discussed.

KEYWORDS: *Universal Design; Set-based Design; Physical Characteristics; Diverse Users*

1.0 INTRODUCTION

Recently, the development of a universal design method that can accommodate user diversity to facilitate adaptation to a worldwide aging society and enable companies to develop effective internationalization strategies has become a priority [1]. Several companies and associations are engaged in the development of products, housing, and workspaces based on the concept of universal design [2]. As one of the measures, to consider individual difference, product is developed based on ergonomics [3]. However, a general design approach that satisfies the needs of diverse users has still not been developed. Designers continue to use trial-and-error processes. Furthermore, the conventional universal design method confines users from the viewpoint of height, body type and age. In this study, a set-based [4] universal design approach for obtaining diverse design solution sets with consideration of the variability of human physical characteristics such as height and weight was proposed. This approach defines user information such as physical characteristics as interval sets; consequently, designers can fully account for user diversity in their product design. The proposed method was applied to a case study of a bicycle frame design problem. Recently, bicycle rental is prevalent centering on urban area and tourist attraction. However, such bicycle is often designed to satisfy confined users in advance. Hence, proposed method aims to obtain design solution sets that all users ride with comfort. In this application, the proposed method defines both the dimensions of bicycle frames and the height of users as design variables and defines the maximum and minimum angles of the knee-joint range of motion as constraint conditions from the viewpoint of human dynamics. The suitability of the proposed design method for obtaining diverse ranged design solution sets calculated by interval arithmetic that accommodate the variability in physical characteristics of diverse users was also discussed.

2.0 SET-BASED UNIVERSAL DESIGN METHOD

2.1 Point-Based Design Method

Traditional design methods are generally based on an iterative process called point-based design [5]. This process uses early design values and runs a simulation. Moreover, the designer evaluates the extent to which the obtained solution satisfies the required performance and constraint conditions. If the obtained point-based design solution does not satisfy the required conditions, it is adjusted iteratively. This process is continued until the point solution satisfies all required performance and constraint conditions. This method is applicable to design processes that are comparatively easy. However, there is no theoretical guarantee that a process will ever converge and produce an optimal solution at the end of the design process when any change of the regained performance and constraint conditions occurs. In addition, it introduces the problem of prolonging the design process because any change of the constraint conditions often necessitates modification of the design. Furthermore, a universal design must accommodate diverse users. Thus, accommodating many users' requirements simultaneously by applying point-based design that incorporates specific user information as a point value is inherently difficult.

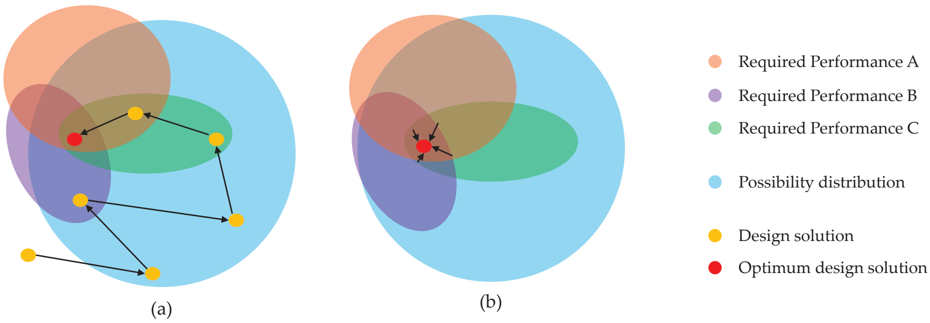

Figure 1: Conceptual diagram of (a) point- and (b) set-based designs

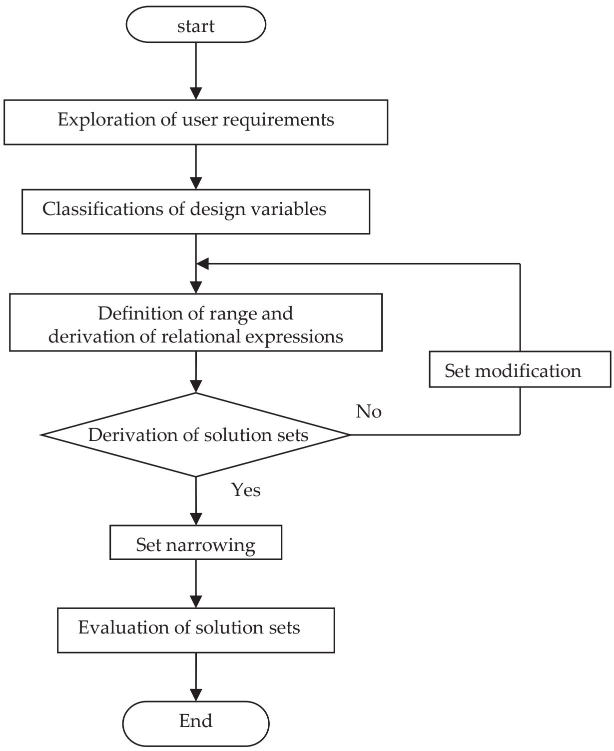

Figure 2: Procedure for the set-based universal design method

2.2 Set-Based Design Method

In contrast to the point-based design method, the set-based design method [6] obtains ranged design solution sets. This method represents all design variables (e.g., physical characteristics, and product features) and the user's requirements including constraint conditions as sets with ranged parameters. Adaptation to the changed design condition is possible because the obtained design solution is defined as a ranged parameter. Furthermore, this method can treat diverse users' characteristics as ranged design variables. In particular, this method enables the development of universal products without the limitation of target users. Figure 1 shows conceptual diagrams of point- and set-based designs.

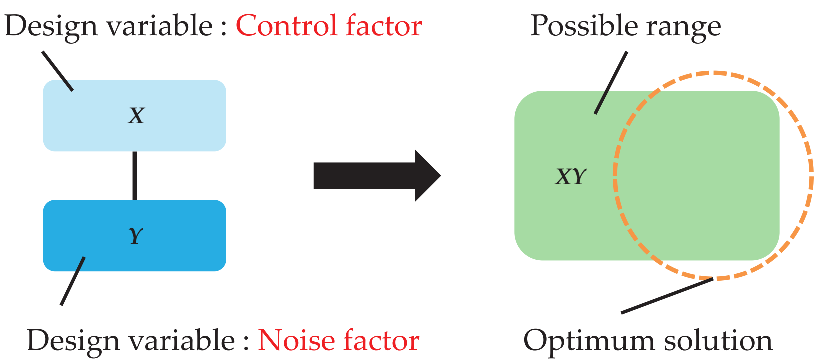

Figure 3: Conceptual diagram of set propagation

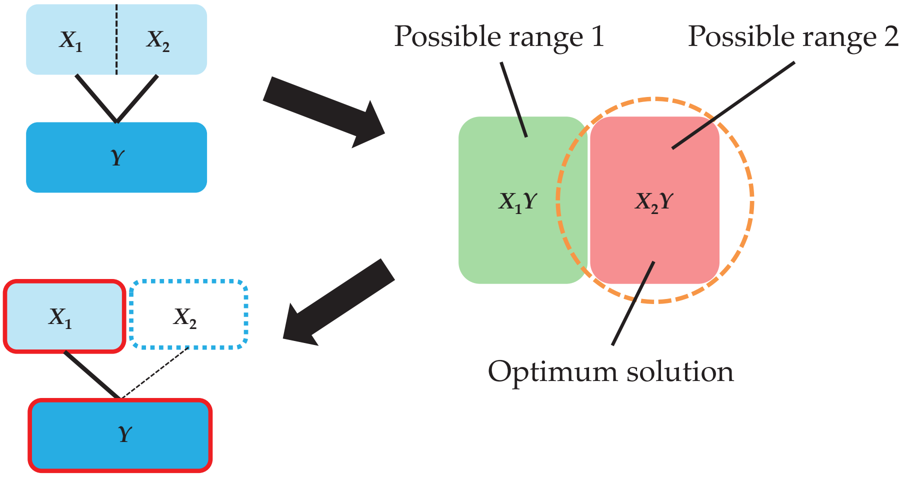

Figure 4: Conceptual diagram of set narrowing

2.3 Proposed Universal Design Method

In this study, a new universal design method for accommodating the physical characteristics of diverse users was proposed. Figure 2 illustrates the procedure for the proposed method which incorporates the concept of a set-based design to satisfy diverse user requirements.

2.3.1 Exploration of User Requirements

At first, the designer explored user requirements and defined them as constraint conditions. The users have diverse requirements with respect to the products. Therefore, in universal design, the designer must consider not only the physical characteristics of users but also user needs in universal design. For example, the rating scale method [7] and the evaluation-grid method [8] are potential exploration methods. The rating scale method and the evaluation-grid method extract user needs. In addition, design variables and requirement performance based on user needs were defined.

2.3.2 Classifications of Design Variables

A designer must consider not only controllable information (e.g., dimensions and weight of the product) but also uncontrollable information (e.g., physical characteristics of users). Therefore, design variables were divided into two types namely control and noise factors. Control factors were designer-controllable variables based on design specifications such as product dimensions, weight, and materials to be used. Noise factors were designer-uncontrollable variables representing user characteristics such as body height and weight.

2.3.3 Definition of Range and Derivation of Relational Expressions

This process added range to design variables and constraint conditions. In addition, the designer initially defined a range sufficiently wide to accommodate diverse users. Moreover, this process developed the relational expressions between design variables and constraint conditions. The range of design variables was defined according to product specifications such as weight or material. In addition, the range of constraint conditions (i.e., the noise factor) was defined on the basis of the human dynamic data such as joint range of motion.

2.3.4 Derivation of Solution Sets and Set Narrowing and Modification

This process derived design solution sets and narrowed them using the set-based design method. In set-based design, design variables were narrowed until the combination of divided design variables satisfied the performance requirements. In contrast, in the case of classified design variables, noise factors were not narrowed. Because this work was based on the radical universal design concept of "satisfy all users," the factors related to user physical characteristics should not be narrowed. Figures 3 and 4 show conceptual diagrams of set propagation and narrowing.

2.3.5 Evaluation of Solution Sets

Obtained design solution sets had wide ranges. To determine the preferred solution sets, the designer defined indices and compared the results for various solution sets. From the viewpoint of human dynamics, exertion force of a joint was one of the indices. In addition, designer created a visualization of design solution sets such as color chart.

3.0 CASE STUDY: BICYCLE FRAME

Recently, rented bicycles have become a prevalent mode of public transportation around the center of towns and leisure venues [9]. However, the number of people who can ride a bicycle is restricted. Thus, in this study, the suitability of the proposed design method was demonstrated by applying it to the design problem of a bicycle frame.

3.1 Evaluation of Solution Sets

A bicycle rental business has a small inventory of bicycles. Thereby, users are partially constrained by this limitation. Hence, assume user requirements is considered. In this work, a user requirement of all users comfortably riding a bicycle was defined.

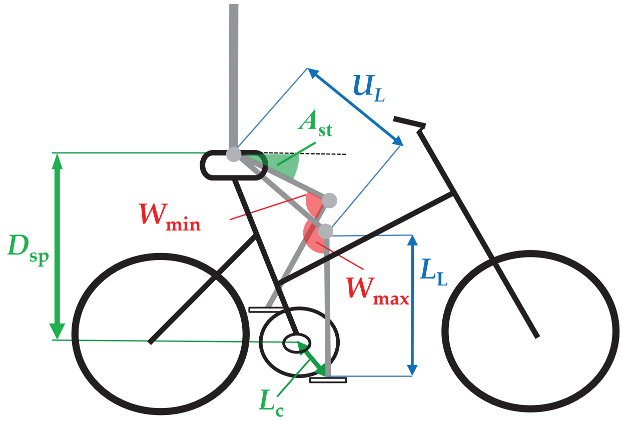

Figure 5: Relations of bicycle and user features

Table 1: Range of each design variables and constraint condition

Type		Name		Range	
				Min	Max
Design variables	Controllable factors (Product information)	Saddle to pedal distance (mm)	*Dsp*	50	200
		Saddle angle (deg)	*Ast*	0	180
		Clank length (mm)	*Lc*	50	180
	Noise factor (User information)	Height (mm)	*h*	1333	1830
Constrained condition		Knee angle (deg)	*W*	50	180

3.2 Classification of Design Variables

The control factors of design variables were defined as follows: saddle angle Ast [deg], saddle-to-pedal distance Dsp [mm], and crank length Lc [mm]. The noise factors of design variables as height H (mm) and the constraint conditions as the range of motion of a human knee joint W [deg] were also defined. Figure 5 shows the relations of bicycle and user features.

3.3 Definition of Range and Derivation of Relational Expressions

Ranges of design variables based on existing bicycle data are defined [10-11]. This study defined design variables with wide range in order to obtain design solution beyond conventional bicycle product. The height of diverse users is defined as the range of all Japanese people's height h ([1333, 1830] mm) according to statistical data [12]. The range of the control factors on the basis of existing product data was also defined [10-11]. In addition, the constraint condition (i.e., knee-joint angle) is defined as closed interval [50, 180] degrees on the basis of previously reported data [13]. Table 1 shows the range of each design variables and constraint condition.

Furthermore, the angles of extended and bent legs were defined as Wmax and Wmin, respectively. In this case study, a strong correlation among height h, upper leg length UL, and lower leg length LL was observed. Therefore, values of UL and LL were approximated as shown in Equations (1) and (2). In addition, knee angles W were defined using trigonometric function of Upper leg length UL, Lower leg length LL and Saddle-to-pedal distance DSP. Equations (3) and (4) show the derivation of the maximum knee joint angle Wmax and the minimum knee-joint angle Wmin.

$$U_L = 0.2184h + 50.91 \tag{1}$$

$$L_L = 0.2294h - 12.512 \tag{2}$$

$$W_{max} = \cos^{-1}\frac{-(\frac{D_{sp}}{\cos A_{st}}+L_c)^2+U_L^2+L_L^2}{2U_LL_L} \tag{3}$$

$$W_{min} = \cos^{-1}\frac{-(\frac{D_{sp}}{\cos A_{st}}-L_c)^2+U_L^2+L_L^2}{2U_LL_L} \tag{4}$$

3.4 Derivation of Solution Sets and Set Narrowing

By applying the aforementioned information to the proposed universal design method, a diverse design solution set was obtained. Figure 6 shows the obtained design solution sets and examples of bicycle frames. By applying the aforementioned information to the proposed universal design method, a diverse design solution set was obtained.

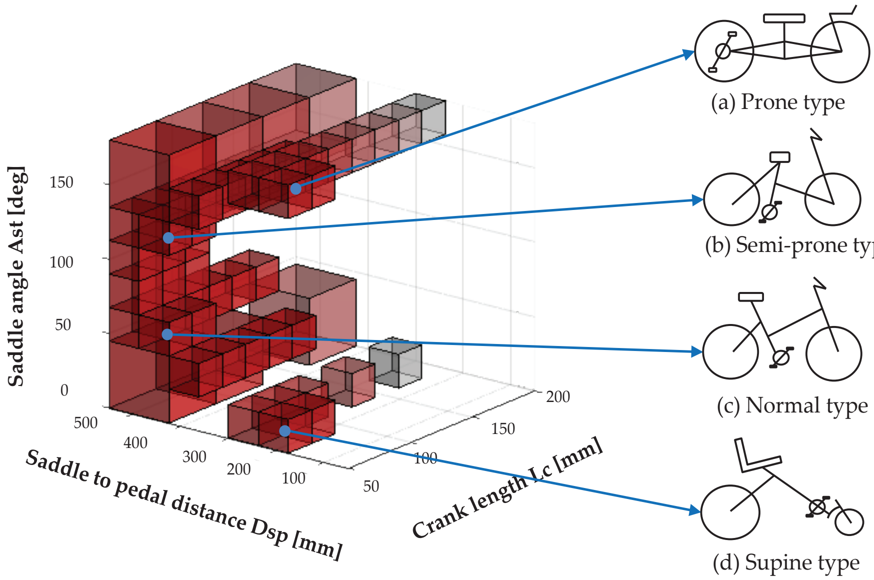

Figure 6: Obtained design solution sets and examples of bicycle frames

3.5 Evaluation of Solution Sets

Finally, the solution sets were evaluated. To evaluate user comfort quantitatively, the solution sets were divided into a scale of 1 to 10 on the basis of knee-power data [12]. The approximated expression in Equation (5) was developed to derive the maximum power of flexed knees M using knee angles w. As the maximum power of flexed knees M has a strong correlation with knee angle based on the human characteristics database [13], the maximum power of flexed knees M by the knee angle was estimated.

$$M = -0.02168w^2 + 4.415w + 84.748 \qquad (5)$$

Furthermore, red-shaded areas in Figure 6 expressed the knee power, where darker-shaded areas indicated greater power. From the obtained design solution sets, the applicability of the proposed method was demonstrated through the design of multiple bicycle frames including four different types of bicycle frames beyond conventional bicycle frames that can accommodate user diversity from the viewpoint of human dynamics.

4.0 CONCLUSION

In conclusion, a set-based universal design method based on the set-based design concept is proposed. In the case study of bicycle frame design, the proposed method leads toward diverse solution sets that accommodate diverse user physical characteristics including unorthodox frame forms which satisfy all users. In addition, the use of added indices to identify preferred solution sets is proposed. Future task is an additional evaluation of sensibility such as comfort [14] and low back pain [15].

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REFERENCES

[1] R. Sims, "Design for all: methods and data to support designers," Ph.D. dissertation, Department of Health Ergonomics and Design, Loughborough University, Leicestershire, UK, 2003.

[2] K. Nakajima, N. Kawabata and T. Tatsumi, "The Studies on the Selling of the Universal Design Goods", Bulletin of the Faculty of Education Mie University Social Science, vol. 60, pp. 135-151, 2009.

[3] T. Chihara, S. Ohyama and A. Seo, "Formulation of Ergonomic Design Problem with Considering the Response to Individual Difference", *Transactions of The Japan Society of Mechanical Engineers Series*, vol. c. 79, no. 799, pp. 800-813, 2013.

[4] M. Inoue, Y. E. Nahm, S. Okawa and H. Ishikawa, "Design Support System by Combination of 3D-CAD and CAE with Preference Set-based Design Method", *Concurrent Engineering: Research and Applications*, vol. 18, no. 1, pp. 41-53, 2010.

[5] M. Inoue, Y. E. Nahm and H. Ishikawa, "Application of Preference Set-Based Design Method to Multilayer Porous Materials for Sound Absorbency and Insulation", *International Journal of Computer Integrated Manufacturing*, vol. 26, no. 12, pp. 1151-1160. 2013.

[6] M. Inoue, Y. E. Nahm and H. Ishikawa, "Collaborative Engineering among Designers with Different Preferences: Application of the Preference Set-Based Design to the Design Problem of an Automotive Front-Side Frame", *Concurrent Engineering: Research and Applications*, vol. 21, no. 4, pp. 252-267, 2013.

[7] N. Yata, T. Furukawa and Y. Manabe, "Determinants of metallic perception based on subjective evaluation (Material Appearance, <Special Issue>Color and Visual Information) ", *Journal of the Color Science Association of Japan*, vol. 37, no. 2, pp. 124-131, 2013.

[8] J. Sanui and M. Inui, "Phenomenological Approach to The Evaluation of Places: A study on the construct system associated with place evaluation: 1", *Transactions of the Architectural Institute of Japan*, vol. 367, pp. 15-22, 1986.

[9] S. Yano, K. Ijiri, S. Nagata, H. Suzuki and S. Fujii, "Promoting Greater Use of Pubic Transports though Rent- a- bicycle System –A Case Study Conducted in the Katsurazaka Area of Kyoto – ", *Material Cycles and Waste Management Research*, vol. 3, no. 22, pp 228-235, 2011.

[10] Japanese Industrial Standards Committee, *Bicycles for General Use (JIS D 9301:2013)*. Tokyo: Japanese Standards Association, pp. 1-94, 2013.

[11] Japanese Industrial Standards Committee, - *Chainwheels and Cranks (JIS D 9415:2008)*. Tokyo: Japanese Standards Association, pp. 1-24, 2008.

[12] National Institute of Technology and Evaluation. (2002). *Human Characteristics Database* [Online]. Available: http://www.tech.nite.go.jp/human/jp/contents/cindex/database.html

[13] K. Yonemoto, S. Ishigami and T. Kondo, "Display and measurement method of joint motion", *The Japanese Journal of Rehabilitation Medicine*, vol. 32, no. 4, pp. 207-217, 1995.

[14] F. Baino, "Evaluation of the relationship between the body positioning and the postural comfort of non-professinal cyclists: a new approach", *The Journal of Sports Medicine and Physical Fitness*, vol. 51, no. 1, pp. 59-65, 2011.

[15] W. Van Hoof, K. Volkaerts, K. O'Sullivan, S. Verschueren and W. Dankaerts, "Comparing lower lumbar kinematics in cyclists with low back pain (flexion pattern) versus asymptomatic controls – field study using a wireless posture monitoring system". *Manual Therapy*, vol. 17, no. 4, pp. 312-317, 2012.