Title:
Path Planning for Product Function Transformation based on Kruskal Algorithm

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Introduction:
A technical system with multi-functions in different environments can meet diversified user needs. State is decided by configurations of this kind of the system in performing a certain type of functions. Transformation refers to a process in which the technical system changes its morphology in order to perform a certain function or improved function [4]. Osprey aircraft, satellite antenna, and Swiss army knife are some examples of transformable systems. The first step of development of a transformable technical system is to plan different function states and paths of state transformations.

Functions of a technical system are designed based on user needs [3], and performed through interactions of the system elements and environments [1]. Diversity needs may come from existing or new users. The needs include different functions in the same environment, the same function works in different environments, or different functions work in different environments, as shown in Figure 1.

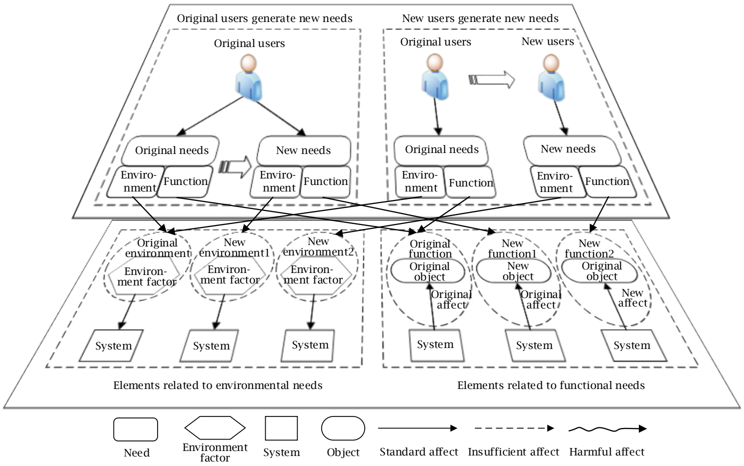

Fig. 1: Product needs and system domains.

Environment refers to related elements outside a system, the object refers to a target of the system. Changes in user needs can lead to changes of the system and object. Changes of environment and object will make it difficult for the technical system to work effectively. The system needs to be redesigned to adapt to the change. Therefore, the basis of designing a transformable system is to find potential environments and objects. Based on the similarity between these factors, distances of potential states are decided using the Kruskal algorithm to search a tree with the shortest distance as the optimal transformation path. A transformable wheelchair is designed to verify the method.

Main Idea:

Distance between environment and object

Features are considered for relationship of the environment and system. Environments can be represented in Eqn. (1).

$$Ei = \begin{pmatrix} e1 & f1 & v1 \\ \vdots & \vdots & \vdots \\ ej & fj & vj \\ \vdots & \vdots & \vdots \end{pmatrix} \tag{1}$$

where *Ei* is the *ith* environment in which the technical system works, *ei* is the *ith* environmental factor, *fi* is the feature of *ei*, and *vi* is the feature value. Similarly, the object is expressed as follows.

$$Oi = \begin{pmatrix} o1 & f1 & v1 \\ \vdots & \vdots & \vdots \\ oj & fj & vj \\ \vdots & \vdots & \vdots \end{pmatrix} \tag{2}$$

A similar environment to the original environment will have a close distance between them, which is easy for their transformation. Relation between environmental distance and similarity is as follows.

$$D(Ei,\ Ej) = 1 - Sim(Ei,\ Ej) \tag{3}$$

Similarly, the relation between distance and similarity between different objects is as follows.

$$D(Oi,\ Oj) = 1 - Sim(Oi,\ Oj) \tag{4}$$

As the environment and object are related to the system, the distance of different forms of the system is decided by Eqn. (5).

$$D(Si,\ Sj) = \frac{D(Ei,\ Ej) + D(Oi,\ Oj)}{2} \tag{5}$$

Environmental factors include different features. If similarity between different features is 0, and r_{ij} is the similarity between features *fi* and *fj,* value *vi* of feature *fi* is in [*a, b*], and value *vj* of feature *fj* is in [*c, d*], the feature similarity can be decided by Eqn. (6).

$$r_{ij} = Sim(fi,\ fj) \tag{6}$$

When $fi \neq fj,\ r_{ij} = 0$. *When* $fi = fj$,

(1)$vi \supseteq vj,\ r_{ij} = \frac{d-c}{b-a}$. (2)$vi \subseteq vj,\ r_{ij} = \frac{b-a}{d-c}$. (3)$vi \cap vj \neq 0$ and $a < c,\ r_{ij} = \frac{b-c}{d-a}$. (4)$vi \cap vj \neq 0$ and $a > c,\ r_{ij} = \frac{d-a}{b-c}$.

(5)$vi \cap vj = 0,\ r_{ij} = 0$.

The similarity between two environments can be decided by Eqn. (7).

$$Sim(Ei,\ Ej) = \frac{\sum r_{ij}}{N} \tag{7}$$

where N is the sum of feature numbers in two environments. Similarly, the similarity of different objects can be decided by Eqn. (8).

$$Sim(Oi, Oj) = \frac{\sum r_{ij}}{N} \tag{8}$$

The distance between two system states can then be decided by Eqns. (1)-(8).

Optimal transformation between different states

A graph *G* (*S*, *D*) can be constructed using the system state as node *S*, and distance between states as edge D. There is a path to pass through all the nodes with the minimum sum of distances, which can be searched by a minimum spanning tree. Different methods have been proposed for solution of the minimum spanning tree, the Kruskal algorithm is most efficient among them as shown in Figure 2 [2].

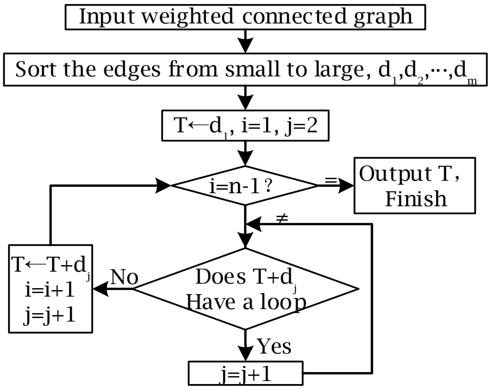

Fig. 2: Flowchart of the Kruskal algorithm.

An optimal transformation path can be found to traverse all states with the minimum distance. The technical system is evaluated by the idealization level as shown in Eqn. (9).

$$I = \frac{\sum U}{\sum H + \sum C} \tag{9}$$

where *I* is the degree of idealization. A large *I* indicates the high value of a technical system. *U* is the benefit of the technical system. In this paper, it is expressed by numbers of environments and objects that the system can adapt. *H* is the harmful function of the system. *C* is cost of the technical system based on the distance between states. In Figure 1, the change of environments and objects may cause their relationship change for the system from a standard affect to a harmful affect. Altshuller proposed 76 standard solutions in TRIZ [5] to be specially used to solve the deficiency or harmful affect between system factors. The application process of the standard solution can assist in the configuration design for each state of the system.

Case study

The technical system of the case study is wheelchair. Users are adults with mobility difficulties. The main environment is outdoor in normal weather conditions. Features and values of potential environments are shown in Table 1.

The features	*E*1	*E*2	*E*3	*E*4	*E*5	*E*6	*E*7
Height of obstacle (*cm*)	[0-3]	[0-30]	[0-3]	[0-3]	[0-1]	[0-1]	[0-1]
Rainfall (*mm/h*)				[2-10]			
Flow rate (*L/min*)							[0-6]
UV index			[5-15]				
Wind velocity				[0-20]			

Tab. 1: Features and values of different environments.

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In Table 1, weather conditions are normal (*E*1), step room (*E*2), outdoor with strong sunshine (*E*3), outdoor with wind and rain (*E*4), indoor (*E*5), toilet (*E*6), and shower room (*E*7). Features and values of potential objects are shown in Table 2.

Features	*O*1	*O*2	*O*3	*O*4	*O*5	*O*6	*O*7	*O*8	*O*9	*O*10	*O*11	*O*12
Horizontal displacement (*m*)	[0-∞]	[0-∞]						[0-∞]	[0-∞]	[0-∞]	[0-∞]	[0-∞]
Supporting capacity (*kg*)	[0-90]	[0-90]	[0-90]	[0-90]	[0-90]	[0-90]	[0-90]	[0-60]	[0-90]	[0-90]	[0-90]	[0-90]
Supporting area (m^2)	[0.1-0.3]	[0.1-0.3]	[0.1-0.3]	[0.11-0.31]	[0.09-0.29]	[0.05-0.15]	[0.2-0.5]	[0.05-0.2]	[0.1-0.3]	[0.15-0.35]	[0.2-0.5]	[0.1-0.5]
Displacement of thigh (*cm*)	[0-5]	[0-5]	[0-5]	[0-5]	[0-5]		[0-5]	[0-5]	[0-5]	[0-5]	[0-5]	[0-5]
Vertical displacement (*m*)		[0-∞]										
Displacement of tableware (*cm*)				[0-1]								
Displacement of axillary (*cm*)						[0-2]						
Displacement of shank (*cm*)							[0-5]			[0-2]	[0-5]	
Displacement of back (*cm*)							[0-5]				[0-5]	
Displacement of head (*cm*)							[0-5]				[0-5]	
Displacement of goods (*cm*)												[0-5]

Tab. 2: Features and values of objects.

Objects in Table 2 include adults travel (*O*1), adults up and down stairs (*O*2), adults sitting (*O*3), adults for meal (*O*4), adults in toilet (*O*5), adults in shower (*O*6), adults in rest (*O*7), children with mobility difficulties (*O*8), adults with upper limb injuries (*O*9), adults with lower extremity injuries (*O*10), comatose adults (*O*11), and goods (*O*12). Through combining environments and objects, a total of 18 potential states are obtained. The distance between states can be calculated by Eqns. (1)-(8), as shown in Table 3.

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16	S17	S18	S19	S20	S21
S1	0	0.12	0	0.14	0.27	0.24	0.55	0.37	0.25	0.39	0.52	0.49	0.49	0.37	0.52	0.65	0.61	0.46	0.55	0.47	0.76
S2	0.12	0	0.12	0.22	0.31	0.32	0.61	0.25	0.37	0.47	0.56	0.57	0.38	0.49	0.59	0.69	0.69	0.58	0.64	0.57	0.74
S3	0	0.12	0	0.14	0.27	0.25	0.55	0.37	0.25	0.39	0.52	0.50	0.49	0.38	0.52	0.65	0.63	0.46	0.55	0.47	0.76
S4	0.14	0.22	0.14	0	0.23	0.29	0.59	0.47	0.39	0.25	0.48	0.54	0.59	0.52	0.38	0.60	0.67	0.58	0.61	0.58	0.79
S5	0.27	0.31	0.27	0.23	0	0.28	0.75	0.56	0.52	0.48	0.25	0.58	0.69	0.65	0.60	0.38	0.71	0.68	0.69	0.77	0.81
S6	0.24	0.32	0.25	0.29	0.28	0	0.65	0.57	0.50	0.54	0.58	0.25	0.69	0.63	0.67	0.71	0.38	0.59	0.63	0.59	0.73
S7	0.55	0.61	0.55	0.59	0.75	0.65	0	0.64	0.58	0.62	0.77	0.68	0.65	0.59	0.63	0.79	0.69	0.69	0.75	0.70	0.81
S8	0.37	0.25	0.37	0.47	0.56	0.57	0.64	0	0.12	0.22	0.31	0.32	0.38	0.49	0.59	0.69	0.69	0.66	0.72	0.65	0.83
S9	0.25	0.37	0.25	0.39	0.52	0.50	0.58	0.12	0	0.14	0.27	0.25	0.49	0.38	0.52	0.65	0.63	0.54	0.63	0.55	0.84
S10	0.39	0.47	0.39	0.25	0.48	0.54	0.62	0.22	0.14	0	0.23	0.15	0.59	0.52	0.38	0.60	0.67	0.66	0.69	0.66	0.88
S11	0.52	0.56	0.52	0.48	0.25	0.58	0.77	0.31	0.27	0.23	0	0.33	0.69	0.65	0.60	0.38	0.71	0.72	0.77	0.85	0.90
S12	0.49	0.57	0.50	0.54	0.58	0.25	0.68	0.32	0.25	0.15	0.33	0	0.69	0.63	0.67	0.71	0.38	0.67	0.71	0.67	0.82
S13	0.49	0.38	0.49	0.59	0.69	0.69	0.65	0.38	0.49	0.59	0.69	0.69	0	0.12	0.22	0.31	0.32	0.70	0.76	0.70	0.84
S14	0.37	0.49	0.38	0.52	0.65	0.63	0.59	0.49	0.38	0.52	0.65	0.63	0.12	0	0.14	0.27	0.25	0.59	0.70	0.60	0.84
S15	0.52	0.59	0.52	0.38	0.60	0.67	0.63	0.59	0.52	0.38	0.60	0.67	0.22	0.14	0	0.23	0.29	0.70	0.74	0.70	0.89

S16	0.65	0.69	0.65	0.60	0.38	0.71	0.79	0.69	0.65	0.60	0.38	0.71	0.31	0.27	0.23	0	0.33	0.80	0.82	0.89	0.91
S17	0.61	0.69	0.63	0.67	0.71	0.38	0.69	0.69	0.63	0.67	0.71	0.38	0.32	0.25	0.29	0.33	0	0.71	0.75	0.72	0.83
S18	0.46	0.58	0.46	0.58	0.68	0.59	0.69	0.66	0.54	0.66	0.72	0.67	0.70	0.59	0.70	0.80	0.71	0	0.14	0.03	0.73
S19	0.55	0.64	0.55	0.61	0.69	0.63	0.75	0.72	0.63	0.69	0.77	0.71	0.76	0.70	0.74	0.82	0.75	0.14	0	0.15	0.76
S20	0.47	0.57	0.47	0.58	0.77	0.59	0.70	0.65	0.55	0.66	0.85	0.67	0.70	0.60	0.70	0.89	0.72	0.03	0.15	0	0.72
S21	0.76	0.74	0.76	0.79	0.81	0.73	0.81	0.83	0.84	0.88	0.90	0.82	0.84	0.84	0.89	0.91	0.83	0.73	0.76	0.72	0

Tab. 3: Distance between states.

The relationship of states can be represented in Figure 3. The minimum spanning tree in Figure 3 can be searched using the Kruskal algorithm for the optimal transformation path shown in Figure 4.

The idealization degree of system states is evaluated by Eqn. (9). The optimal path, I_A=4.7, compared to the original path I_B=0.22, obviously, $I_A > I_B$.

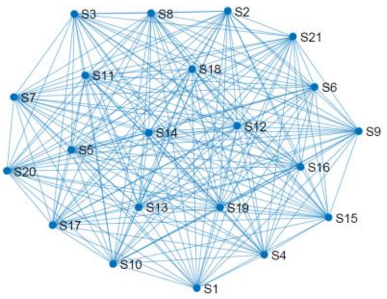

Fig. 3: Relationship of states.

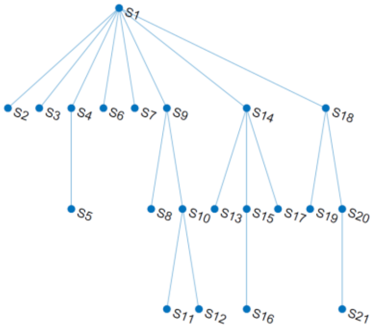

Fig. 4: The optimal transformation path.

Following the above method, each state of the transformable wheelchair is designed using the standard solution as shown in Figure 5.

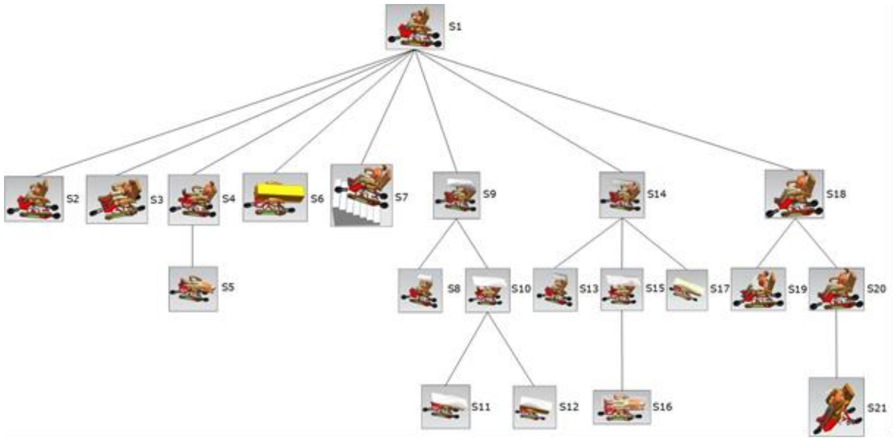

Fig. 5: Wheelchair model on optimal transformation path.

Conclusion:

In this research, potential environments and objects are determined according to diversity needs of product. Distances between potential states of the system are obtained based on the similarity. The optimal transformation path of states is planned to save resources and simplify transformation operations. Future work will model the wheelchair to illustrate the effectiveness of the proposed method.

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