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ORIGINAL ARTICLE

Simultaneous functional synthesis of mechanisms with mechanical efficiency and cost

Bin He · Pengchang Zhang · Lilan Liu

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Abstract The functional synthesis of mechanisms is involved in the problem solving process to finding functional chains of mechanisms in conceptual design, which has an essential effect on the product innovation. However, existing approaches for functional synthesis of mechanisms are either inextensible to achieve functional chains of complex mechanisms or prone to a loss of optimal solutions under the consideration of mechanical efficiency and cost. This paper is devoted to a systematic dynamic programming-based methodology for constrained functional synthesis of mechanisms with the consideration of mechanical efficiency and cost. After a general functional representation model based on the motional element pair is proposed, an exhaustive dynamic programming functional synthesis algorithm of two motional elements pair is then proposed to produce functional chain solutions with consideration of mechanical efficiency and cost. The functional synthesis of new devices for jacking up system of an offshore platform is given as an example, which demonstrates that the methodology is obviously helpful to produce valuable functional chains of mechanism solutions with consideration of mechanical efficiency and cost.

Keywords Functional synthesis · Functional chains · Mechanism synthesis · Mechanical efficiency · Cost · Constrained weighted directed graph

1 Introduction

The functional synthesis of mechanisms is an early stage in the problem-solving process to finding functional chains in conceptual design, which requires evaluation and selection in addition to this in order to complete conceptual design of mechanisms [1, 2]. Current researches in functional synthesis of mechanisms can be classified as the process-oriented synthesis approach and the case-oriented synthesis approach.

The process-oriented approach synthesized desired functions with a set of functional elements since existing mechanisms are composed of a set of functional elements. Kota and colleagues [3, 4] proposed a matrix-based functional model and corresponding reasoning approach to automated synthesis of mechanisms. Chakrabarti and colleagues [5, 6] synthesized solution concepts using functional elements and their combination rules to produce an exhaustive set of solution concepts. Tang [7] achieved an automated conceptual design of mechanical systems using kinematic functions. Yan and Chui [8] proposed generalized kinematic chain-based mechanism synthesis algorithm. Lipson [9] explored some representations for kinematic synthesis using genetic programming. Some results from this research include automated morphological matrix generation from the design repository [10], more expansive overall concept generation algorithms based on the empirical knowledge of function-component connections in the form of relational matrices [11], and graph grammar rules [12, 13]. We also have developed an improved morphological matrix-based synthesis approach for achieving conceptual design of mechanisms [14].

The case-oriented synthesis approach achieved functional synthesis through the synthesis of mechanism prototypes, which refers to the generalized mechanism knowledge abstracted from design cases [15]. These methods use a variety of computer techniques including case-based reasoning [16], constraint programming [17], qualitative symbolic algebra [18], geometric algebras [19, 20], or ontology [21]. Welch and Dixon [22] developed a behavior graphs approach for design synthesis of predefined embodiments. Schmidt and Shetty [23] put forward a graph grammar methodology for structure synthesis of mechanisms with automated isomorphism detection.

Since the energy crisis is gaining increasing global concerns in recent years, the energy conservation approaches to product design are being investigated to decrease the energy

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B. He · P. Zhang · L. Liu (✉)
Shanghai Key Laboratory of Intelligent Manufacturing and Robotics, School of Mechatronic Engineering and Automation, Shanghai University, 149 Yanchang Rd., Shanghai 200072, China
e-mail: cadteach@163.com

consumption. As about 70 % of the cost is determined in conceptual design [24], which is also one of the key factors to success in the market, reducing the cost of a product in conceptual design is an effective way [25, 26]. As functional synthesis of mechanisms plays a crucial role in conceptual design [27], it is a valid approach for energy conservation and market competition integrating functional chain solutions with optimal mechanical efficiency and cost in conceptual design. However, the current approaches could achieve combinatorial exhaustive solutions, while the absence of mechanical efficiency and cost constraints; thus, how to produce optimal functional chain solutions of mechanisms with higher mechanical efficiency and lower cost is an important issue in the current crisis. Therefore, it still makes great sense to develop a new methodology for functional synthesis of complex mechanisms with consideration with mechanical efficiency and cost.

The paper is devoted to a dynamic programming-based functional synthesis approach, which can allow exhaustive functional synthesis of mechanism prototypes and the generation of optimal solutions with two constraints of high mechanical efficiency and low cost.

The rest of the paper is organized as follows: Section 2 proposes a functional representation model based on the input and output motional element pair. Section 3 proposes weighted directed graph-based representation model for functional synthesis of mechanisms under the consideration of mechanical efficiency and cost. Section 4 proposes a design catalogue-based model to represent mechanism prototypes. This paper suggests such an algorithm using dynamic programming, which is one of many approaches solving weighted constrained shortest path problem (WCSPP) efficiently [28–30]. WCSPP requires considering both the cost and the mechanical efficiency constraint. We suggest a dynamic programming algorithm, so designers can minimize cost and maximize the mechanical efficiency simultaneously. As a dynamic programming algorithm, the label setting algorithm (LSA) is selected for the constrained weighted shortest path problem because this algorithm developed in [31] is regarded as the most effective dynamic programming approach algorithm for the WCSPP. Section 5 proposes a dynamic programming-based functional synthesis approach integrated with mechanical efficiency and cost. With the functional synthesis of new devices of jacking-up instrument of offshore platform as an example, Section 6 is shown to demonstrate the methodology proposed in this paper. Then, Section 7 concludes this paper.

2 A motional vector pair-based functional representation model

2.1 Motional vector model

The function can usually be formally represented as the relationships between the input and output state of a system to meet the user's requirements [32–34]. The motion can always be regarded as motional vector of input and output motion [35], while involving many features, such as type, direction, magnitude, constancy, orientation, continuity, intermittence, reciprocation, etc. Thereby, only four fundamental features of them are selected as crucial variables in this paper to represent motions in a qualitative way, which is named as motional vector. The four characters are as follows:

Type, orientation, direction, and reciprocator

The features almost include all the functional attributes of the mechanism elements. The meaning of the features are coded as follows:

1. Type: A motion can be classified as rotation motion, translational motion, and helical motion, referring to the motion type of the input and output of a mechanism coding with by R, T, H, respectively.
2. Orientation. The orientation of a motion can be defined as X, Y, or Z in the Cartesian coordinate, while that of a rotation or a helical motion can be defined with its axis.
3. Direction: For a translation along or counterclockwise rotates around the positive axis in the Cartesian coordinate, its direction can be defined as +1, otherwise −1. When a motion is to-and-fro, its direction is set as 0.
4. Reciprocator: It refers to whether the input and output of the motion can back and forth or not; yes and no are coded with 1, −1.

With the above features, a motion can be qualitatively represented with a motional element [type, orientation, direction, and reciprocator].

2.2 Motional vector pair-based functional model

A function can be formally represented as the transformation of motional vector, named as a motional vector pair, which is composed of input motional vector and output motional vector: $[\text{type, orientation, direction, reciprocator}]_{\text{input}} \rightarrow [\text{type, orientation, direction, reciprocator}]_{\text{output}}$. For instance, the function of a cam-follower mechanism, as shown in Fig. 1, can be represented as [R,X,+1,–1]→[T,Y,+1,–1].

3 Graph-based representation model for functional synthesis of mechanisms

As each motional vector has limited variables, such as R, T, X, −1, +1, etc., it is easy to list all possible motional vectors in an exhaustive way, then link these motional vectors with a directed arc with a corresponding number array (M_{ij}^{k}, C_{ij}^{k}, S_{ij}^{k}) to demonstrate its mechanical

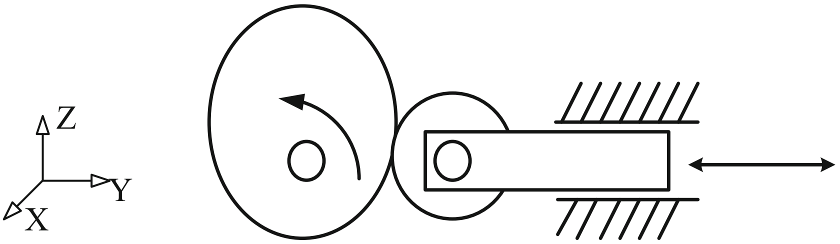


Fig. 1 The representation of a function achieved by a cam-follower mechanism

efficiency, cost, and corresponding serial number in knowledge base. In this way, a weighted directed graph is established and defined as design solution space [36], as shown in Fig. 2.

1. Node: The node v_i or v_j represents a motional vector.
2. Directed arc: A directed arc is used to be declared a mechanism to achieve the transformation from a source motional vector to destination motional vector.
3. Number array $(M_{ij}^{k}, C_{ij}^{k}, S_{ij}^{k})=\{(m_{ij}^{1}, c_{ij}^{1}, s_{ij}^{1}), (m_{ij}^{2}, c_{ij}^{2}, s_{ij}^{2}),\ldots, (m_{ij}^{k}, c_{ij}^{k}, s_{ij}^{k})\}$:
   (a) Mechanical efficiency M_{ij}^{k}: The number $M_{ij}^{k}=\{m_{ij}^{1}, m_{ij}^{2}, m_{ij}^{3},\ldots,m_{ij}^{k}\}$ in these directed arcs is used to represent the mechanical efficiency of the corresponding mechanism achieving the transformation from a source motional vector v_i to destination motional vector v_j.
   (b) Cost: The number $C_{ij}^{k}=\{c_{ij}^{1},c_{ij}^{2},c_{ij}^{3},\ldots,c_{ij}^{k}\}$ in these directed arcs is used to represent the costs of the corresponding mechanism achieving the transformation from a source motional vector v_i to destination motional vector v_j.
   (c) Serial number: The serial number $S_{ij}^{k}=\{s_{ij}^{1},s_{ij}^{2},s_{ij}^{3},\ldots,s_{ij}^{k}\}$ in these directed arcs is used to represent the serial number of corresponding mechanism prototypes achieving the transformation from a source motional vector v_i to destination motional vector v_j in the knowledge base.

In the above representations, i stands for the number of source motional vector node and j stands for the number of destination motional vector node, while k stands for the number of the corresponding mechanism achieving the transformation from the source motional vector v_i to destination motional vector v_j since there might be several solutions to achieving the this transformation.

For instance, the function of a mechanism with no. 101 in design knowledge base is [R,X,+1,–1]→[T,Y,+1,–1]; thus, node v_i represents source motional vector [R,X,+1,–1] and its destination motional vector v_j is [*T*, Y,+1,–1]. The corresponding $(m_{ij}^{k}, c_{ij}^{k}, s_{ij}^{k})$ in the directed arc is noted with (0.8, 120, 101), which means the mechanical efficiency of the mechanism is 0.8, while the cost of the mechanism prototype is $120, and the serial number is 101 in knowledge base. As there are many solutions to achieving from two motional element nodes, there might have an arc with several data $(m_{ij}^{k}, c_{ij}^{k}, s_{ij}^{k})$.

4 Representation of mechanism prototypes

Design catalogue, proposed by Roth [37], is used to establish the knowledge base. An improved design catalogue integrating the motional vector-based knowledge is proposed with identity, function, body, constraint, and evaluation item. The identity has the basic information of mechanism prototype, such as the name and the serial number, just the same as the serial number in the above-weighted directed graph. The representation of a cam-follower mechanism as an example is shown in Table 1.

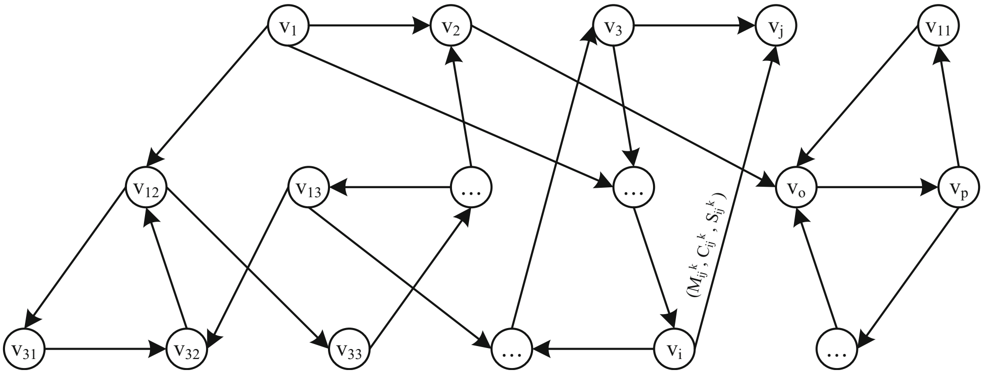
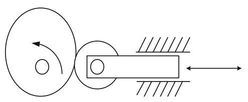


Fig. 2 Graph-based representation model for functional synthesis of mechanisms

Table 1 A representation model of cam-follower mechanism based on design catalogue

Identity	Serial number	20	Name	Cam-follower mechanism
Function	Input motional vector	[R,X,+1,-1]	Output motional vector	[T,Y,+1,-1]
Body	Structure		Main design parameters	Base diameter: D; Offset distance: e; Roller radius: r, etc.
Constraint	Accuracy	High	Intermittence	High
	Transmission distance	Short	Efficiency	<0.95
	Self-lock	False	—	
Evaluation	Accuracy	Moderate	Reliability	Moderate
	Environmental suitability	Good	Safety	High
	Reuse ability	Good	—	

5 Functional synthesis based on weighted directed motional functional graph

The mechanical efficiency and cost are important factors in mechanism transmission, so how to integrate functional synthesis of mechanisms with mechanical efficiency and cost is an important issue. After a designer inputs a desired function with the input and output motional vectors, the dynamic programming-based functional synthesis based on the above-weighted directed graph [38] is with a result of possible functional chains for the achievement of the desired function. In Fig. 2, a weighted directed graph G(V,E) is given with a weight function (m_{ij}^{k}, c_{ij}^{k}, s_{ij}^{k}) that maps each arc (v_i, v_j) to a real-valued weight array, which is the mechanical efficiency, cost and the corresponding number in the knowledge base of mechanism prototype. A minimum weight path from destination motional vector u to source motional vector v in G(V,E) is to be found to solve the functional synthesis of mechanisms. Therefore, the problem is formulated in this paper as a multi-objective routing problem in weighted directed graph. We will introduce how the above steps are fulfilled in details in the following.

5.1 Mathematical formulation of WCSPP

As the total mechanical efficiency η is calculated as the multiplication among mechanical efficiency η_i at each of the stages, i.e., $\eta=\eta_1*\eta_2*\ldots*\eta_i*\ldots*\eta_n$. As $\log_{0.5}\eta=\log_{0.5}(\eta_1*\eta_2*\ldots*\eta_i*\ldots*\eta_n)=\log_{0.5}\eta_1+\log_{0.5}\eta_2+\ldots+\log_{0.5}\eta_i+\ldots+\log_{0.5}\eta_n$; thus, the value of $\log_{0.5}\eta_i$ is used as the transformed weight from actual weight η_i. To maxim the total mechanical efficiency η is equivalent to minimize the sum of ($\log_{0.5}\eta_1+\log_{0.5}\eta_2+\ldots+\log_{0.5}\eta_i+\ldots+\log_{0.5}\eta_n$), as the y=log0.5(x) is decreasing function monotonically.

The constrained shortest path problem, with relationship between mechanical efficiency and cost, which is an extended shortest path problem, is generally known as the NP-hard problem [39]. The objective function of WCSPP linear programming formulation-based mechanism design, its constraints, and variables are defined as follows.

$$
\begin{aligned}
&\min\sum_{a\in A} c_a x_a\\
&s.t.\ \sum_{a\in\delta^{+}(i)} x_a-\sum_{a\in\delta^{-}(i)} x_a=\begin{cases}1, & if\ \ i=s;\\ -1, & if\ \ i=t;\\ 0, & if\ \ i\in V\backslash\{s,t\};\end{cases}\qquad \forall i\in V\\
&\sum_{a\in A} w_a x_a\le W_c\\
&x_a\in\{0,1\},\quad \forall a\in A
\end{aligned}
\tag{1}
$$

and

$$
\begin{aligned}
&\min\sum_{a\in A} (\log_{0.5} m_a) x_a\\
&s.t.\ \sum_{a\in\delta^{+}(i)} x_a-\sum_{a\in\delta^{-}(i)} x_a=\begin{cases}1, & if\ \ i=s;\\ -1, & if\ \ i=t;\\ 0, & if\ \ i\in V\backslash\{s,t\};\end{cases}\qquad \forall i\in V\\
&\sum_{a\in A} (\log_{0.5} w_a) x_a\le W_m\\
&x_a\in\{0,1\},\quad \forall a\in A
\end{aligned}
\tag{2}
$$

in which

c_a: cost at arc a
x_a: when transported from arc a m,1 or 0
m_a: mechanical efficiency at arc a
w_a: constraint at arc a
W_c: cost constraint
W_m: mechanical efficiency constraint
$\delta^{+}(i)$: It denotes the set of arcs leaving node i, ie, $\delta^{+}(i)=\{(i, j)\in A\}$, for each $i\in V$.
$\delta^{-}(i)$: It denotes the set of arcs entering node i, ie, $\delta^{-}(i)=\{(j, i)\in A\}$, for each $i\in V$.

The objective function which minimizes cost as in (1) considered mechanism cost in all these arcs in the reachable paths. When minimize $\log_{0.5}m_a$ (maxim mechanical efficiency) as in the objective function in (2), all the mechanical efficiencies in the reachable paths were considered. The constraints of (1) and (2) are the same form, but the constraint W_c in (1) is cost, and the constraint W_m in (2) is mechanical efficiency.

5.2 Functional synthesis based on weighted directed motional functional graph

As a solution for the dynamic programming algorithm, this study has used the label setting algorithm, which was developed by Descrochers and Soumis [31]. This method attaches labels to each node, and the labels are composed of a pair {weight, objective function}. In the label setting algorithm, mechanical efficiency was weighted as a constraint, and cost was expressed as the objective function. Therefore, the effective cost range obtained in the WCSPP linear programming model is imposed as the weight of the label setting algorithm.

In the label $\{M^q_i, C^q_i\}$, W^q_i refers to the qth mechanical efficiency in the node i, and C^q_i refers to the qth cost in the node i. m_{ij} and c_{ij} refer to the mechanical efficiency and cost from node i to node j, and L_i refers to the ith laber, respectively. The label setting algorithm is generally performed as follows.

```
Step 1: Initialization.
Set N as stages of mechanical transmission.
Set $L_s = \{(0, 0)\}$, and set $L_i = \Phi$ for all $i \in V \backslash \{s\}$.
Step 2: Selection of the label to be treated.
If all Labels have been marked, then
{
    Stop, all efficient labels have been generated;
}
Else
{
    Choose $i \in V$ such that there's unmarked label in $L_i$ and $M^q_i$ is minimal, where q
    is the path that attains this weight value.
}
Step 3: Extend label $(M^q_i, C^q_i)$
for all $(i, j) \in \delta^+(i)$ with $M^q_i + m_{ij} \le M$ do
{
    If $(M^q_i + m_{ij}, C^q_i + c_{ij})$ is not dominated by $(M^k_j, C^k_j)$ for $l \in I_j$
    Then
        {
        set $L_j = L_j \cup \{(M^q_i + m_{ij}, C^q_i + c_{ij})\}$
        Update $I_j$ accordingly.
        }
}
Mark label $(M^q_i, C^q_i)$.
Goto Step 2.
Step 4: List all the path based on the stage N of mechanical transmission.
```

The label setting algorithm is easier to understand and implement. In practice, in the case of a large network, large problem set, people usually use label setting algorithm since it is easier to maintain the entire graph, and it is more efficient to update the data in a graph rather than converting a graph into a linear program system.

6 Application

To achieve the functional synthesis of mechanical transmission system with the constraints of mechanical efficiency and cost, jacking up system of offshore platform is given as an example to illustrate the proposed methodology. With the ocean exploration, it is necessary to develop a self-elevating jacking up to elevate the platform to a certain height from the sea and support the operation of the whole platform in the sea as well.

Since the input motional vector can be [R,X,+1,–1], the output motional vector should be [T,Z,+1,–1] respectively. Therefore, the desired mechanism should be able to achieve the functions: [R,X,+1,–1]→[T,Z,+1,–1]. Here, [R,X,+1,–1]→[T,Z,+1,–1] is selected as the functional requirement.

Set the stage of mechanical transmission $N=2$. It carries out exhaustive functional synthesis, resulting in a set of possible functional chains, such as [R,X,+1,–1]→[R,Y,+1,–1]→[T,Z,+1,–1], [R,X,+1,–1]→[T,X,+1,–1]→[T,Z,+1,–1], [R,X,+1,–1]→[R,X,–1,–1]→[T,Z,+1,–1], [R,X,+1,–1]→[R,Z,+1,–1]→[T,Z,+1,–1], [R,X,+1,–1]→[R,Z,–1,–1]→[T,Z,+1,–1], [R,X,+1,–1]→[R,Y,–1,–1]→[T,Z,+1,–1], [R,X,+1,–1]→[R,Y,–1,+1]→[T,Z,+1,–1], etc.

Set the stage of mechanical transmission $N=3$. It carries out exhaustive functional synthesis, resulting in a set of possible functional chains, such as [R,X,+1,–1]→[R,Y,+1,–1]→[T,Y,+1,–1]→[T,Z,+1,–1], [R,X,+1,–1]→[R,Z,+1,–1]→[R,Y,–1,–1]→[T,Z,+1,–1], [R,X,+1,–1]→[R,Y,–1,–1]→[R,Z,+1,–1]→[T,Z,+1,–1], [R,X,+1,–1]→[R,Z,–1,–1]→[R,Y,–1,–1]→[T,Z,+1,–1], [R,X,+1,–1]→[T,Y,+1,–1]→[R,Y,+1,–1]→[T,Z,+1,–1], [R,X,+1,–1]→[T,X,+1,–1]→[R,X,+1,–1]→[T,Z,+1,–1], [R,X,+1,–1]→[T,Y,–1,–1]→[R,X,+1,–1]→[T,Z,+1,–1], etc.

After evaluating the above feasible solutions with respect to the predefined performance criteria, the combination, "Crank-slider+worm+reduction gears Pair" is selected as the optimal solution. This combination is eventually developed as a device prototype, as shown in Fig. 3.

7 Conclusions

This paper presents a new systematic dynamic programming-based methodology for functional synthesis of mechanisms with the considerations of mechanical efficiency and cost. After a general functional representation model based on the motional element pair is proposed with a result of the motional functional graph, an exhaustive dynamic programming functional synthesis of two motional elements pair is then proposed to produce solutions with the considerations of mechanical efficiency and cost. The conceptual design of new devices of jacking up instrument for offshore platform was given as an example, which demonstrates that the methodology is obviously helpful to produce valuable functional chains of mechanism solutions for high mechanical efficiency and low cost.

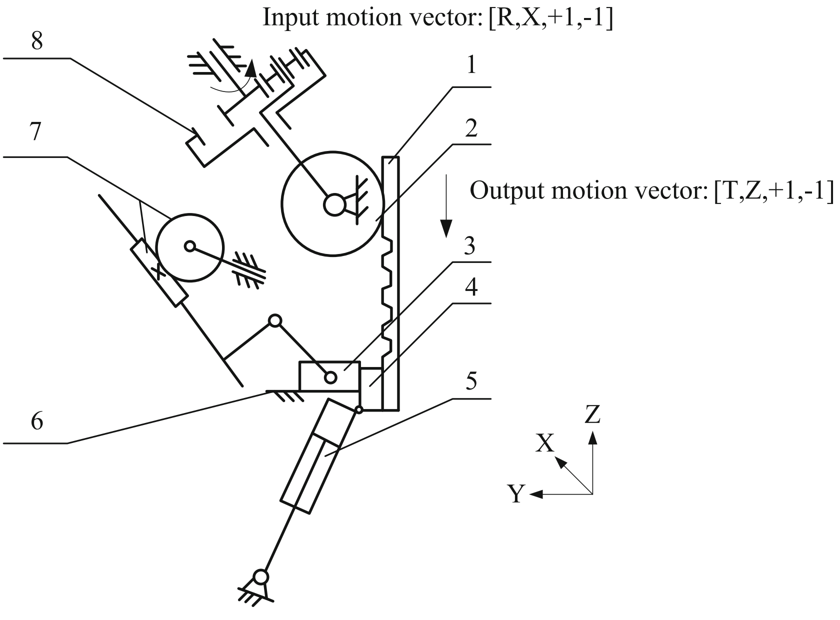


Fig. 3 The sketch of a jacking up instrument. *1* rack, *2* climbing gear, *3* slider, *4* locking bezel, *5* hydraulic cylinder, *6* slider support plate, *7* worm, *8* reduction gears

Three concepts have been applied to the State Intellectual Property Office of China for patents.

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References

1. Deng YM, Zhu YM (2009) Function to structure/material mappings for conceptual design synthesis and their supportive strategies. Int J Adv Manuf Technol 44(11–12):1063–1072
2. Chakrabarti A (2002) Engineering design synthesis: understanding, approaches and tools. Springer
3. Krishnan G, Kim C, Kota S (2012) Building block method: a bottom-up modular synthesis methodology for distributed compliant mechanisms. Mech Sci 3:15–23
4. Chiou SJ, Kota S (1999) Automated conceptual design of mechanisms. Mech Mach Theory 34:467–495
5. Chakrabarti A, Bligh TP (1996) An approach to functional synthesis of mechanical design concepts: theory, applications, and emerging research issues. Artif Intell Eng Des Anal Manuf 10:313–331
6. Chakrabarti A, Srinivasan V, Ranjan BSC, Lindemann U (2013) A case for multiple views of function in design based on a common definition. Artif Intell Eng Des Anal Manuf 27(3):271–279
7. Tang L (2008) An approach to function identification in automated conceptual design of mechanism systems. Res Eng Des 19(2–3): 151–159
8. Yan HS, Chiu YT (2013) An algorithm for the construction of generalized kinematic chains. Mech Mach Theory 62:75–98
9. Lipson H (2008) Evolutionary synthesis of kinematic mechanisms. Artif Intell Eng Des Anal Manuf 22:195–205
10. Bohm MR, Vucovich JP, Stone RB (2008) Using a design repository to drive concept generation. J Comput Inf Sci Eng 8(1):014502
11. Skander A, Roucoules L, Meyer JSK (2008) Design and manufacturing interface modelling for manufacturing processes selection and knowledge synthesis in design. Int J Adv Manuf Technol 37(5–6):443–454
12. Wu ZH, Campbell MI, Fernandez BR (2008) Bond graph based automated modeling for computer-aided design of dynamic systems. J Mech Des 130(4):1–11
13. Zhang WY, Tor SB, Britton GA (2005) A graph and matrix representation scheme for functional design of mechanical products. Int J Adv Manuf Technol 25(3–4):221–232
14. Chen Y, Feng PE, He B, Lin ZQ, Xie YB (2006) Automated conceptual design of mechanisms using improved morphological matrix. J Mech Des-T ASME 128(3):516–526
15. Zhang WY, Tor SB, Britton GA (2001) A prototype knowledge-based system for conceptual synthesis of the design process. Int J Adv Manuf Technol 17(8):549–557
16. Han YH, Lee K (2006) A case-based framework for reuse of previous design concepts in conceptual synthesis of mechanisms. Comput Ind 57:305–318
17. Subramanian D, Wang CS (1995) Kinematic synthesis with configuration spaces. Res Eng Des 7(3):193–213
18. Williams BC (1990) Interaction-based invention: designing novel devices from first principles. In Expert Systems in Engineering Principles and Applications, 119–134. Springer
19. Palmer RS, Shapiro V (1993) Chain models of physical behavior for engineering analysis and design. Res Eng Des 5:161–184
20. Goel AK (1991) A model based approach to case adaptation. Proceedings 13th Annual Conference of the Cognitive Science Society 1991, Lawrence Erlbaum
21. Afacan Y, Demirkan H (2011) An ontology-based universal design knowledge support system. Knowl-Based Syst 24:530–541
22. Welch RV, Dixon JR (1994) Guiding conceptual design through behavioral reasoning. Res Eng Des 6(3):169–188
23. Schmidt LC, Shetty H (2000) A graph grammar approach for structure synthesis of mechanisms. J Mech Des 122(4):371–376
24. Ullman DG (1992) The mechanical design process. McGraw-Hill
25. Xu Y, Elgh F, Erkoyuncu JA (2012) Cost engineering for manufacturing: current and future research. Int J Comput Integr M 25:300–314
26. Saravi M, Newnes LB, Mileham AR (2013) Using Taguchi method to optimize performance and product cost at the conceptual stage of design. P I Mech Eng B-J Eng 227(9):1360–1372
27. Pahl G, Beitz W, Wallace K (2007). Engineering design: a systematic approach. Springer
28. Androutsopoulos KN, Zografos KG (2009) Solving the multicriteria time-dependent routing and scheduling problem in a multimodal fixed scheduled network. Eur J Oper Res 192:18–28
29. Dumitrescu I, Boland N (2001) Algorithms for the weight constrained shortest path problem. Int Trans Oper Res 8(1):15–29
30. Cho JH, Kim HS, Choi HR (2012) An intermodal transport network planning algorithm using dynamic programming—a case study: from Busan to Rotterdam in intermodal freight routing. Appl Intell 36(3): 529–541
31. Descrochers M, Soumis F (1988) A generalized permanent labeling algorithm for the shortest path problem with time windows. Inf Syst Res 26:191–212
32. Vermaas PE (2013) The coexistence of engineering meanings of function: four responses and their methodological implications. Artif Intell Eng Des Anal Manuf 27(3):191–202
33. He B, Song W, Wang YG (2013) A feature-based approach towards an integrated product model in intelligent design. Int J Adv Manuf Technol 69:15–30
34. He B, Feng PE (2013) Guiding conceptual design through functional space exploration. Int J Adv Manuf Technol 66:1999–2011
35. He B, Lv HF, Song W (2012) Space matrix-based conceptual design of mechanisms. Int J Adv Com Tech 4(13):123–130
36. Nahm YE, Ishikawa H (2006) Novel space-based design methodology for preliminary engineering design. Int J Adv Manuf Technol 28(11–12):1056–1070
37. Roth K (1993). Konstruieren mit Konstruktionskataloguen. Springer
38. Diestel R (2005). Graph Theory. Springer
39. Chang TS (2008) Best routes selection in international intermodal networks. Comput Oper Res 35:2877–2891