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Chapter

Task-Based Conceptual Design of a Novel Product

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Abstract

A novel task-based conceptual design method introduced around a decade ago has been presented from its most characteristic points including the general idea, usage and modification of previous art, usage and modification of independent sets of functional and mechanical means for implementation of those functions, creation of intermediate mechanical-functional sets supporting the development of new structures like models, visualization of the design process, and so on. The current paper aims to reveal a non-computerized graphically visualized set of actions covering all the above-mentioned major steps of the suggested methodology. The success of synthesizing action greatly depends on the method of creation submechanisms or virtual mechanisms, which are making possible visualization and consideration intermediate structures helping to identify and implement a necessary function. The method of creating of such subcategories and application of elementary movements or set of links for explaining or satisfying demanded set of functions could be considered the main methodical novelty and strength of proposed conceptual design method. Two examples are included: the first reinvention of a known tool—Locking Pliers from database and second synthesis of a novel hand tool—Adjustable Nut Wrench.

Keywords: conceptual, design, task, structure, modification

1. Introduction

The conceptual phase of design still remains as the most challenging and less understood steps of general mechanical design. The difficulties of its description and formulization are coming from first the nature of conceptual design, implying search of a novel structure with novel properties among theoretically large number of candidate solutions, and secondly from the individual nature of designing process, depending on design tradition, skill, and experience of the designer. Design process being very attractive and creative by its definition may bring the designer more results and satisfaction if organized in a way to free the designer from the routine task of checking a large number of options with necessary efforts of visualization. The designer will greatly win if only decision-making duty from a limited number of candidate solutions will be left on his side. Combinational methods widely used for novel structure solution search are effective for the automatic organization of search process with minimum human involvement; however they are providing solutions for a key or major function, only suggesting modifications within fixed topology with randomly generated accompanying functions with a high probability of negative functions among them. The fact of single or key function consideration in

combinational search dramatically lowers its methodical strength because any design process is valued for providing a multifunctional solution but not valued for the fact of generation from a single topology. A novel conceptual design is generally preceded by an act of making a decision which is possible after managing large data of previous knowledge and search of candidate solutions of the current design process. The success of large data management depends on the success of turning large data into small-sized easily manageable portions of information or models. From category point, the models should serve both categories involved, namely, functions and mechanism to provide interdependence and simultaneous consideration of those two, and from application point, they need to serve both classic actions of design-synthesis and analysis—including such segments of design as database analysis and creation of supplementary virtual mechanisms with the latest further update into structures, satisfying the given design tasks. That's practically an impossible task to understand and manage a designer's own plan during his or her efforts to create a novel mechanism. Commonly a designer who puts an aim to create a new mechanical structure or to update an existing one relies on proved by own practice and experience approaches and scenarios which could be basically different from each other and normally not shared with designers' community. For the past few decades, due to growing demand on fresh products with advantageous proprieties and because of wider application of digital technologies, the challenge of better organization of conceptual design process becomes more actual, and this demand was satisfied by several approaches and methodologies. The task-based design methods can be conventionally divided into methodologies based mostly on human participation or on computer-aided methods with minimum involvement of human factor. Some examples for the second group of task-based design methodologies are quite successful when directing a designer to organize a new product development with novel properties [1–3]. Very popular and classical methods [4, 5] of splitting mechanical components from functional ones have clear abstraction and visualization means and require consideration of a large number of candidate solutions in an attempt to isolate a workable and optimal one. A fundamental publication [6] is using analyses of the vast engineering database as a source for a novel product design, where the search trend implies consideration of either combination of various movements of basic links or direct search of solutions among existing solutions. Insufficient level of abstraction and visualization narrows the opportunities of processing and getting optimal results among mechanical means, having required functions and properties. Any design methodology can be evaluated by the number of essential design tasks considered during a mechanism synthesis process and distribution of those tasks along with steps of conceptual design: more tasks involved provides wider and full satisfaction of design aim with a maximum number of demanded properties of a novel product. When following [4, 5] methodologies, there is a great risk of missing and/or canceling consideration of essential features on one side and necessity of implementing of an exhausting search of candidate solution on the other. The largely popularized method of Theory of Inventive Problem Solving (TRIZ/TIPS) is quite effective for finding solutions of conceptual design and resolving invention tasks [7, 8]. A contradiction matrix and set of 40 creative/inventive tools are used for developing special auxiliary structures—VEPOLS (a Russian abbreviation of substance + field)—as a model of future novel product for revealing new and neutralizing the harmful functions. That's very common in mechanical engineering practice that an innovative solution surfs out once a limited set of various requirements are considered simultaneously, thus facilitating the creation of a decision-making situation. In the TIPS case, the fact of usage of a cumbersome set of 40 tools and no necessary relation of this set to the essence of the main problem generally may lead to comprehensive search with a broad number of possible results.

A task-based methodology of conceptual design [9] developed as a result of long-term engineering experience has proven its efficiency in the development of numerous and various mechanical devices based on interdependent and direct consideration of two sets of components—mechanical and functional—in a state when those components are processed to design models, facilitating their application or further modification for satisfying a current design task, while the remaining ones are planned to be satisfied by similar modification actions. Work models are developed at consecutive steps of the design process which may have different contents depending on the step, level, and scale of the design task.

In Sections 2.1 and 2.2, flat graphs are used for describing key mechanical and functional models; then the same graphs are used for visualizing modification (expansion and squeezing) of those models for serving different design needs. In Section 2.3 the development of local mechanical and functional models is presented; Section 2.4 covers developments for a solution means, namely, resources of database and resources of synthesis tools and similar developments for functional sets. Section 3 is, for example, relating to the reinvention of a known tool—locking pliers —from patent database, and finally, Section 4 is for the set of design cycles of conceptual design for a specific hand tool: self-adjustable nut wrench.

1.1 Tasks and objectives

The task of this paper is to provide clear graphical presentation and visualization for steps of the proposed approach of conceptual design methodology through mechanisms, functional-mechanical graphs, and set of hierarchized functions to control and manage the process of conceptual design, starting from the task on it and finishing with novel structure satisfying the pre-given tasks on development.

2. Main ideas of conceptual design method described by mechanical-functional graphs

2.1 Key models containing mechanical and functional categories

For mechanical categories the graph (**Figure 1**) has two vertices for links L1 and L2 related to each other by an edge as a kinematical joint in general or as another relation R12 in a way that this relation may satisfy or plan satisfaction of demanded function F12. In fact, the links L1 and L2 are connected through two paths, firstly the edge F12 represents the function as a subject of satisfaction, while the edge R12 represents the mechanical or physical means needed for satisfying the demanded function. At the implementation stage, F12 could be replaced by a physical kinematical joint shown in square symbol as R12.

For functional categories the graph (**Figure 2**) visualizes the step of getting a translated function F2 from function F1, where edge T12 stands for a translating operator, while the physical implementation of function F2 is supposed to be done through mechanical means M12, represented by the second edge in the graph (**Figure 2**). That's easy to notice the topological analogy between **Figure 1** and **Figure 2**. Vertices of graph in **Figure 2** also are connected through two paths, firstly by the edge representing the translating operator T12 providing a child function F2 which may be implemented in contrary to function F1 and secondly including second edge M12 representing the mechanical mean for such implementation. R12 in square symbol in **Figure 2** stands for the type of relation between functions F1 and F2.



Figure 2. Graph model for functional set.

It is worthy to note that both models include two initiating components, which in the mechanical model can be interpreted as a necessity of two links for getting a movement between them to implement a function. Analogously in the functional model, the presence of two functions can be interpreted as a necessity for having at least a function next to the initial function to provide its implementation by mechanical means. Generally, a single function also may serve as a task for development; anyhow a two-function model is considered to keep topological similarity of two basic models and also for presenting the translator operator which has the analogy to the relation of the links in the mechanical model in **Figure 3**.

The graphs in **Figures 1** and **2** are confirming the main idea of the proposed method of direct interdependence between mechanical and functional means for the fact of the presence of a functional edge in mechanical graph and presence of a mechanical edge in the functional graph. By the progress of the design process, the edges for functional graphs should be gradually substituted by physical relations between the links, and thus a novel mechanical structure should be generated at the end of design.

Structurally both design components' links and functions are centrally located in both graphs, leaving the left cells for relations between components and the right cells for the purpose of the means of implementation of those relations.

Other characteristic properties of the concept design method—interdependence of mechanical and functional categories and therefore possibility of combined consideration as a condition of target-oriented organization of conceptual design process—can be topologically visualized by the insertion of functional contents from



Figure 3. *Combined mechanical graph.*

Figure 2 into the functional edge in **Figure 1**, thus getting combined mechanical functional graph (**Figure 3**), and correspondingly by inserting mechanical contents of the graph (**Figure 1**) into the mechanical edge of the functional graph (**Figure 2**), thus getting combined functional-mechanical graph (**Figure 4**).



2.2 Models describing modification of mechanical and functional categories by means of expansion and squeezing

Once model graphs (**Figures 1–4**) are setting contents (centrally located) and relation (located on the left and right sides) of components of mechanical and functional matrices, expansion and squeezing actions aim to set synthesis preparation step. Those actions aim to establish the necessary scope of the search in a manageable way, avoiding exponential growth of components which leads to an exhausting search of sought solution. For the case of mechanical graph (**Figure 6**), the action of expansion results in necessary multiplication or addition of number of links in the central graph with an indication of mutual relation presented by a generalized symbol of *R18* (**Figure 5**). For the case of a functional graph, the same similar action leads to necessary multiplication or addition of the number of functions generated in an attempt to have the chance of their satisfaction by mechanical graph (**Figure 6**). Symbol *T18* stands for generalized translation operator between



Figure 5. Graph model for expansion and squeezing of mechanical means.

functions *F1 and F8*. Graphs (**Figures 5** and **6**) can show the expandable and squeezable nature of both mechanical and functional entities by a simple modification—multiplication of number of links and multiplication of the number of functions. Along with multiplication, the edges of graphs should provide connections for both links and functions, thus confirming the function-based modification for the mechanical graph case and confirming the generation of new functions in the functional graph case. The opposite action of subtracting the links and functions will relate to squeezing case.

The combination of edges *F12* from **Figure 5** and M12 from **Figure 6** helps to compose combined expanding-squeezing model as shown in **Figure 7**.

Represented modifications of both mechanical and functional means have the ability to disclose the hidden functional resources of the mechanical side and hidden ways of mechanical implementation of the functional side. Accordingly, both models have the ability of concentration of a limited number of links for mechanical side, creating local mechanical models and for a concentration of a limited number of functions for creating a local set of functions subject to implementation.

The case when the mechanical set consists of just one link may be interpreted as the squeezed down the state of set of links which were initially connected by a set of relations and then unified into a single link after consideration and implementation of those functional requirements. The mechanical set (**Figure 5**) can include the entire set of concept design components when the generalized function is substituted by its contents from **Figure 6**.



Figure 6. *Graph model for expansion and squeezing of functions.*



2.3 Development of mechanical and functional models as preparation for synthesizing action

The modification of mechanical and functional sets is following different design goals: search and disclosure of hidden resources—in case of expansion and localization of the task and in case of squeezing. In both cases, interdependent portions of mechanical means and functions are being isolated. Those portions are easily manageable for analyzing the function implementation scenarios and for building a new structure with new properties. As described above isolated portions of mechanical/ functional sets are called models which are concentrating the main problem at a current design state, separating the problem from the general design process.

Localization and isolation of a problem are a widely practiced [3, 6, 7] action in mechanical design, supporting the task concentration, task targeting, and finding a solution. Anyhow the approach based on freedom and possibility of management and modification of two sets of mechanical and functional means in a direct and interdependent way, which opens a large-scale opportunity for finding an optimal solution; avoiding a large-scale exhausting search makes the proposed approach advantageously and effectively different from the abovementioned task localization approaches and design procedures. Thereby, two fragments of links $L3 \dots L6$ and functions $F3 \dots F6$ from **Figure 8** are separated and localized from general mechanical (M) and functional (F) sets. The isolated fragments thus are containing a low number of links and functions, and they are isolated in a way to focus designer attention on a finding of a solution of an isolated or targeted objective function. The isolated fragments of mechanical means contain links which either have the ability



Figure 8. Graph representation of two localized fragments (models) in mechanical and functional sets.

to satisfy the sought function or may gain this ability after proper modification, adding links, chains, grouping links, etc.

Localization of *mechanical and functional* fragments relates not only to neighbor components as it stated for convenience and simplicity but to any combination of components from **Figures 5** and **6**.

2.4 Database modification and usage as a means for synthesizing action along with other synthesizing tools

The model presented in Figure 8 serves the formulation of the problem and setting objective of synthesis which should be searched or prepared, depending on its availability in database or by satisfying challenging function by an initiated movement of a link. In other words, the first action relates to the search and to the usage of a confirmed function from database, which in wider interpretation can be considered as known mechanisms or fragment of mechanisms, and for the second case, setting a movable link originated from the basic one in a way to provide one of the common mechanical primitive functions (cam, screw, lever, gear, etc. mechanisms). The second action relates to a donation of degree of freedom action, where the movement of the novel originated link relative to the basic link may be interpreted in a wider range of functions than normal, in which it is interpreted by the designer. It is worthy to emphasize that same modeling techniques for mechanism and function (Figures 1 and 2), modification (Figures 5 and 6), and modeling (Figure 8) combined as a task block of conceptual design are identically applicable for a solution means. Corresponding models (Figures 1, 2, 5, 6 and 8) are valid for solution block, and those models could be developed using the same abovedescribed procedure and modification techniques. Once a solution block is developed upon requirements of conceptual design, then this block could be aggregated with links of the preparation and task setting block. Graphically this aggregation is shown in Figure 9 where two identical per-content and per-development procedure blocks stand on the left and right sides relative to centrally located aggregation symbols AMD (A for aggregation, M for mechanical block, D for database or solution block) which are representing edges of the graph, connecting corresponding links from task preparation block and solution block.



Figure 9. Model for aggregation graph connecting task solution preparation block on the left and database or solution block on the right.

3. Application task-based conceptual design method on analyses and reinventing of a locking pliers (US patent, 1970)

3.1 Eight sets of design cycles

Eight sets of design cycles below track the concept design or redesign of a known tool locking pliers patented in the USA in 1970. The process starts with

setting of objectives for design and ends with the structural diagram. Each design cycle is provided by explanations cited in **Figures 10–17**. Each design cycle shows the degree of implementation of design goal starting from 0 and ending with 1 (100%).



Figure 10.

This is a task for synthesis; four basic functions are set as subject for implementation. Lock an object, provide adjustable thickness of locked object, develop necessary pressure for locking, and release the object if necessary. Functions are weighed by proportional values. Each design cycle shows status of a specific function implementation. Zero means function is planned but not implemented, empty cell means function is not planned, and the presence of a numerical value shows implementation.



Figure 11.

This design cycle is for planning such feature on convenient usage as holding in one hand while locking an object and releasing the object upon necessity.



Figure 12.

Adjustable feature as well the object locking feature are provided by pivoting Jaw1 against Jaw2, an action which can be explained also by an action of granting DOF.



Figure 13.

Property of developing pressure is implemented by an action of inserting a fragment of four bar mechanism, which at the region of end point is able to generate high force by lower amount of movement; a special virtual mechanism is developed (b, c) for explanation and confirmation of high transmission ratio feature.

4. Conceptual design example for a self-adjustable nut wrench

4.1 Task of conceptual design

The presented example of conceptual design refers to the search and finding a solution for a unique structure hand tool—a self and fast action adjustable socket—nut wrench [10]. According to its features, it replaces a large socket set for both metric and English sizes, differs in its features and outer look from any similar



Figure 14.

Development of virtual mechanism for explaining the locking-fixing function of locking pliers. The virtual mechanisms provides confirmation and positive usage of locking force and neutralization of a force that attempts to release and cancel locked condition of locking pliers.



Figure 15.

A slider is provided for connecting rod, allowing to achieve the adjustable feature of locking pliers.

purpose hand tool in the market, and serves as a frequently used tool for a household user. A comparison list of two products is shown in **Table 1**.

Two features of this new creative hand tool are planned and structurally implemented. Novel features of self-adjustable nut wrench are quick- and selfadjustment and one-hand operation. The disadvantage is lower level of torque ability. The adjustable nut driver (known product) has slower adjustment action, high torque, and the necessity of two-hand operation for adjustment of the distance between the jaws. It has no self-adjustment feature and human control is needed for adjustment.

The original stage of design includes situation when one of the main features of one hand operation should be revealed and described by virtual mechanisms. For that reason, the palm and three fingers of human hand namely little finger, index



Figure 16.

A new link L_{13} is arranged between the lower handle and connecting rod to allow the mechanism to be released from a locked state when the release button is triggered.

	Mechanism Diagram			Set of Links			Functional Graph				
DESIGN CYCLE 8			$L_1.Up_1$ $L_2.Lo_1$ $L_3.Ob_1$ L_4Har $L_5.Pa$ $L_8.Thr$ $L_7.Ind$ $L_{16}.Lit$ $L_{17}.Ri$ $L_{18}.Mi$ $L_{19}.Inr$ $L_6.Pa$ $L_{15}.Ha$	L ₁ .Upper Jaw L ₂ .Lower Jaw L ₃ .Object to be Locked L ₄ Hand-Right L ₅ .Palm-Right L ₇ .Index Finger-Right L ₁₆ .Little Finger-Left L ₁₇ .Ring Finger-Left L ₁₈ .Middle Finger-Left L ₁₉ .Index Finger-Left L ₆ .Palm-Left L ₁₅ .Hand-Left			$\begin{array}{c} \begin{array}{c} \begin{array}{c} \begin{array}{c} \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\$				
	DESIGN CYCLE	Weight		2	3	4	5	6	7	8	
	F ₁ .Lock an Object	0.1	0	0	0.1	0.1	0.1	0.1	0.1	0.1	
	F ₂ Hold in Hand	0.1	0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	
	F ₅ .Develop Pressure	0.4	0			0.4	0.4	0.4	0.4	0.4	
	F ₃ .Adjustable Thickness of Object	0.2	0		0.1	0.1	0.1	0.2	0.2	0.2	
	F ₄ .Release	0.2	0	0.1	0.1	0.1	0.1	0.1	0.2	0.2	
	Plan / Implementation	1/1	1/0	1/0.2	1/0.4	1/0.8	1/0.8	1/0.9	1/1	1/1	

Figure 17.

This design cycle is revealing the inconvenience of using the locking pliers for release function; so far two hands are needed for this operation.

finger and palm of human hand are described by granting one-degree movements duplicated by drive chains each of them attached to the future handle of future tool to implement four functions: holding, adjustment, screwing, and releasing operations by a single hand. So the model at this stage of conceptual design includes human hand, handle of the tool, nut, bolt, ground floor, human feet, human body, and the chain, which is closed at the already mentioned human hand.

The next set of functions lying in the model for action synthesis of the mechanism responsible for fast, not reversible, and secure adjustment holding the nut head during screwing operation needs to be inserted in a block located between the first set of functions. The third set of featured relates to the portioned rotation of

Adjustable nut driver: known product	Self-adjustable nut wrench: new product
Two-hand usage	One-hand usage
Not so convenient	Convenient
Adjustable	Adjustable
Slow adjustable	Quick adjustable
Heavy duty	Light duty
Ratcheting	Ratcheting
Higher torque	Lower torque
Not convenient to release	Convenient to release
Not easy ratchet adjustment	Easy ratchet adjustment
Range of adjustment: wide	Range of adjustment: narrow
Two-hand adjustment is needed	Self-adjustable

Table 1.

Feature list of existing and new nut wrenches.

screw or the nut head that leads to the accomplishment of ratcheting function. Implementation of the ratcheting feature is missing in the current set of design cycles. Detailed implementation inside each set of functions is based on building of an open chain or elementary set of sliders and rotational links denoting specific functional meaning to each of them and then continued by attempts to accomplish those movements by the synthesis tools of grating degrees of freedom, by freezing of movements, duplicating by parallel chains, and conditioning by drives.

4.2 Ten sets of design cycles for conceptual design of self-adjustable nut wrench

Below 10 steps of conceptual design for the novel tool per predefined features are listed. Explanations for each step are cited in **Figures 18–27**.



Figure 18.

The first design cycle is setting objectives of design, listed red highlighted in the section state of function. The links involved in the design are connected in a way to plan implementation of required functions.



Figure 19.

The second design cycle is for modeling nut rotation operation, including necessary functions of nut rotation and axial sliding because of screw movement.



Figure 20.

The third design cycle serves for building a virtual mechanism, providing convenience of usage due to holding of the tool in one hand and providing full control during nut tightening and releasing operations.

5. Conclusions

1. The study is devoted to the development of a more visualized environment for conceptual design, based on mechanical diagrams, mechanical-functional graphs and models, and concept design result evaluation based on weighted functions.



Figure 21.

The fourth design cycle is for providing convenient usage of the tool when adjusting opening between the jaws by pressing on the tool by right hand thumb while holding the body of toll by palm and two fingers of the same right hand.



Figure 22.

The feature of adjustable size for a nut is planned in this design cycle. Jaws are separated from the socket base to allow adjustable feature. Still unknown connection between the jaws and socket body is symbolized by parallel lines urging to touch each other and belonging to neighbor links.

- 2. Mechanical diagrams are broken down and equipped with virtual mechanisms for detailed revelation of hidden functions for a more comprehensive consideration of functions and finding ways for their satisfaction.
- 3. Mechanical and functional graphs are built in a way to express both structural contents of mechanism and functions subject to implementation in both the planning state and implementation state.



Figure 23.

The design cycle shows an implementation step of planned function (adjustable). Jaw L_{12} is linked rotationally to the socket base L_3 . The graph shows this rotational connection by R_{312} symbol continued from symbol of planned function F_3 .



Figure 24.

The mechanical set is expanded by means of a sleeve L_{13} being in proper connection with the socket base and jaw which provides necessary functions of locking a nut, irreversible lock, self-adjustable feature, and still keeping the major function of the adjustable. This design function is a planning step for red highlighted functions.



Figure 25.

At this design step, the four functions planned previously (design cycle 7) are implemented. Physical kinematical joints marked in square symbols are connecting links L_3 , L_{12} , and L_{13} to provide required functions F_{15} , F_{16} , F_{17} , and F_{18} .



Figure 26.

The design cycle provides necessary connections between human hand finger socket base and sleeve for convenient control over jaw opening.



Figure 27.

Physical implementation of functions planned in design cycle 9 by duplicating functional edges of the graph with cam, rotational, and prismatic kinematical joints.

- 4. An exemplary set of design cycles is presented for serving needs of reverse engineering or reinventing of a known product, demonstrating, analyzing, and explaining possibilities of the method applied to a known product.
- 5. A hierarchical set of the traditional presentation of functions and its evaluation is upgraded into a matrix formatted table, allowing to track step-by-step implementation of tasks, still keeping hierarchical relations and numerical evaluation of conceptual design tasks at each step of the design cycle.
- 6. The same visualized approach is applied for structural synthesis of a novel product based on novel advantageous features and based on property comparison with a competitive product.

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