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Citation	JSME international journal. Series C, Mechanical systems, machine elements and manufacturing. 2001, 44(3), p. 782-792
Version Type	VoR
URL	https://hdl.handle.net/11094/3474
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A Configuration Synthesis Method of Mechanism Systems Using Motion Marker Sequence and Planar Cells*

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We discuss the design synthesis problem of mechanical systems with an example of configuration design of chain-type mechanisms. Mechanisms are used as system elements in various products, and each mechanism system is composed of mechanism pairs. In the design process, the functional structure of mechanisms and their spatial configuration are determined. The former means the sequential chains of pairs, and the latter means the arrangement and geometry of mechanism elements. We propose a framework for simultaneously considering both issues for designing a certain level of complicated mechanism systems. The concepts of marker sequences and cell-based planar representation are introduced to manipulate a design. Each marker corresponds to an abstracted representation of a particular mechanism element. Each cell corresponds to a region for such a marker. The computational design process is organized by generating marker sequences, assigning markers to cells, refining both of them, and embodying the configuration and arrangement of mechanisms. Finally, a prototype CAD system implemented under the proposed concepts is applied to several design examples. In the conclusion, we show the necessity of fictitious media for representing and computerizing the conceptual and configurational phases of a design process.

Key Words: Design Engineering, Computer Aided Design, Mechanism Synthesis, Conceptual Design, Configuration Design, Function Structure, Spatial Arrangement, Chain-Type Mechanisms, Marker and Cell

1. Introduction

In designing a mechanical system, its functional structure as a system must be determined based on the design requirements, the configuration and geometry of respective system elements must be arranged, and further the overall spatial arrangement as a complete system must be adjusted. This type of design problem includes various issues involving multiple granularity levels and multiple disciplines. Multiple viewpoints and criteria are necessary for representing design objects and evaluating design results. It is important to consider such issues individually and to coordinate their coupling toward achieving globally integrated design results(1),(2). When the design process is being unfolded to some degree, that is, when the details of a design are materializing, the definition of relatively concrete models for physical entities becomes realizable, and the design contents are investigated and manipulated using such models. In contrast, what is called conceptual or configurational design process is the phase for preparing the bases for constructing those concrete models. Therefore, it is difficult to represent the design contents and design knowledge for conceptual and configurational design phases. This is the main cause of computerization difficulty of design activities in the early phases of the design

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* Received 28th November, 2000. Japanese original: Trans. Jpn. Soc. Mech. Eng., Vol. 66, No. 642, C (2000), pp. 673-680 (Received 25th November, 1998)

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process.

We define systems that transfer motion or power from one position to another or mechanically control devices through chained pairs of mechanisms as "*chain-type mechanisms,*" and discuss the configuration design synthesis problem of their functional structure and spatial arrangement in order to develop fundamental concepts of computational methods for conceptual and configurational design phases of mechanical systems. In the following sections, we first propose an abstracted representation scheme for chain-type mechanisms with motion markers and planar cells. Second, we explore a design computation framework for configuration synthesis under such abstraction. Third, we implement a prototype CAD system and apply it to some design-problems. Finally, we conclude this study with some perspectives toward computerization of the early phases of the design process for not only mechanism systems but also mechanical systems.

2. Interaction between Functional Structure and Spatial Configuration in Mechanism Systems Design

2.1 Design conditions of mechanism systems

The primary roles of mechanisms in a mechanical system are to activate devices or control systems by somehow transmitting kinematic motion or force from a mover to a follower through intermediate connectors. While the major design conditions straightforwardly correspond to the fundamental functions of mechanism primitives, i.e., mechanical pairs, other subsidiary design conditions are indispensable to establish a design result as a physically feasible artifact beyond major ones. In detail, the following kinds of design conditions should be integrally considered to totally design mechanism systems:

- *Primary conditions on the combination of mechanism pairs* ··· The sequence of mechanism pairs as a series of intermediate connectors must satisfy the kinematic configuration that is indicated between the mover and the follower.
- *Subsidiary conditions for the combination of mechanism pairs* ··· Such sequence must be configured in order to control motion timing, force magnitude, etc. at the position of the follower.
- *Coordination of a series of mechanism subsystems* ··· The motions among different subsystems must be properly synchronized in the cases of one-input multiple-output mechanism systems.
- *Spatial arrangement condition of mechanism elements* ··· The mechanism elements that compose a sequence can exist as physical entities in the entire design space. This includes the regional conditions for the motion trajectory of respective elements, the conditions for avoiding any interference during the travel of elements, and so forth. This point differentiates the design problem of mechanism systems from other arrangement problems of conventional machines without any internal motion.
- *Optimality of a mechanism system* ··· The overall system must meet various criteria to achieve total optimality, such that each pair should be moderately simple, the number of pairs should be small, etc.

2.2 Mutual coupling between functional structure and configurational arrangement

The integrative circumstances of the above conditions indicate mutual dependence among them. That is, the spatial arrangement design of mechanism elements requires a sequence of mechanism pairs as a prerequisite, but the selection of each mechanism pair requires some information about the surrounding spatial situation where it will be arranged afterward. Therefore, it may be necessary to refine the mechanism sequence that has been designed under the functional requirements, or it may be required to modify the functionality of an entire series of primitive pairs in order to meet the spatial conditions, for instance, by inserting another new mediating pair into a sequence to adjust the position of some followers within the overall layout space.

The above issue means that the design process of mechanism systems cannot be simply divided into a one-directional sequence of conceptual design for a functional system structure, preliminary design for a spatial arrangement, etc. In other words, the contents for functional structure and those for spatial arrangement are mutually coupled. Therefore, it is indispensable to manipulate both issues somehow with coordination in designing mechanism systems.

2.3 Multidisciplinarity and granularity levels

Functional structure and spatial arrangement mentioned above are related to each other through different disciplines. When globally and locally recognizing such mutual coupling across disciplines, the representation schemes that are independently suitable for manipulating respective disciplines are not sufficient. In other words, representation of design contents and formalization of design process require any framework that can properly manage internal issues under cross-disciplinarity in addition to inner-disciplinary issues.

When viewing a chain-type mechanism system as a functional system, it can be represented by multiple ways of respective mechanism chains, individual mechanism elements that compose the chains, and their detailed attributes such as the size and dimensions of respective elements. On the other hand, the spatial arrangement can be represented by various levels and means from the outline of the entire system to the detailed geometric information of individual elements as well. The hierarchical diversity of these representation media is abstractly understood with the concept of granularity levels(1),(2) in knowledge representation and design inference.

Among various representation media, solid modeling techniques are available for precisely representing the geometry of individual elements. They enable strict evaluation of design conditions and so forth in detail design phases. However, they are not suitable for efficiently representing the outline of the entire arrangement and the shape of individual functional elements in the corresponding granularity level. In order to coordinately manipulate mutually coupled issues, especially in any computational design framework, it is necessary to provide some symbolically abstracted representation scheme and corresponding design procedures that meet with the diversity across different disciplines and multiple granularity levels.

3. Mechanism System Representation with Motion Markers and Planar Cells

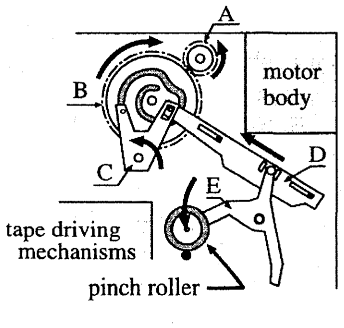
3.1 Abstraction in mechanism system representation

For the introduction of any symbolically abstracted representation scheme, we review the practical circumstances of mechanism systems design with a concrete example.

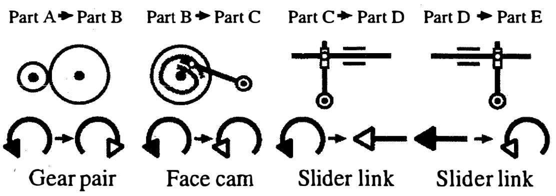
Figure 1 illustrates an experimental abstraction of a pinch-roller pressing mechanism used in a videocassette recorder, to investigate its functional structure and spatial arrangement. Figure 1(a) shows an existing design result concretely. As for the functional structure, as shown in Fig. 1(b), the speed of rotational motion provided by element 'A' is reduced through a gear pair, the action timing, trajectory distance, etc. are adjusted by the cam element between 'B' and 'C', and then motion is transmitted to the follower's position at 'E' through two slider-clank mechanisms: 'C and D' and 'D and E'. In this case, the spatial relationship between the mover 'A' and the follower 'E' is a dominant factor affecting the designed mechanism sequence beyond purely functional requirements. On the other hand, it may be reasonable to introduce a shape for recognition of spatial representation and design, as shown in Fig. 1(c), that is, the overall space is globally divided into a set of small rectangular regions and each functional element is assigned to one of the divided cells.

Under the above experimental abstraction, we first introduce "*motion marker*" in order to symbolically represent the fundamental functions and outlined shape of individual mechanism elements, which directly correspond to the recognition of Fig. 1(b). Then, the sequence of such markers is called "*marker sequence*," which corresponds to the functional structure of an overall mechanism system. As for spatial arrangement, it is assumed that small regions in the layout space are restricted to rectangles, the examples of which are shown in the abstraction of Fig. 1(c), to efficiently model the spatial configuration information in its conceptual and qualitative level. Then, we name such rectangles "*cells*." These concepts translate the design problem of chain-type mechanism systems to an iterative process of generating marker sequences, assigning markers to cells and so forth.

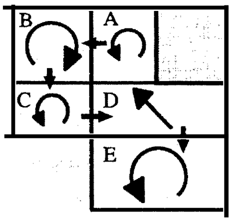
Besides, the concept that the entire space is divided into a set of rectangular cells or compartments has been used in several types of layout design



(a) Pinch-roller pressing mechanism



(b) Sequence of mechanism pairs



(c) Mechanism element arrangement in cells

Fig. 1 Functional structure and configurational arrangement of a mechanism

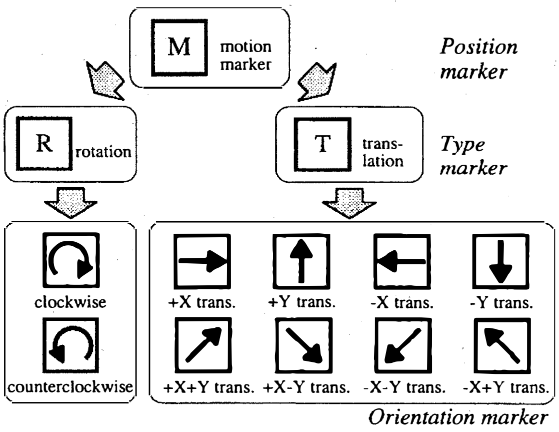


Fig. 2 Motion marker levels

problems, such as for plant components(3), pipe routing design of energy plants(4), etc. Its advantage is the extraction of essential parts from target information processing through the elimination of superfluous parts from complicated spatial information. Such extraction makes design computation possible and efficient. However, what the rational abstraction of spatial information is remains another question behind such advantage. For instance, in the case of plant layout design, it is reasonable to divide the entire space into rectangular compartments of the same size due to the nature of a plant building. We introduce here the cell representation as aforementioned because it is expected to be simple and efficient, although its rationality has not been clearly explained as compared with the case for plant layout design.

3. 2 Roles and attributes of motion markers

Figure 2 shows the motion markers introduced based on the aforementioned viewpoint. The definition of markers is primarily categorized into the following three levels so that the marker selection design is formulated as a particularization process of markers from the upper level to the lower one.

Position ··· A marker that indicates only the arrangement position of a mechanism element. Each of them is simply assigned to a particular cell within the entire space.

Type ··· A marker that further indicates the functionality of a mechanism element; that is, whether it is a rotational element or a translational element. Under the given marker sequence and the assignment of respective markers to cells, the type of each marker can be determined by their corresponding relationships.

Orientation ··· A marker that furthermore indicates the orientation of each marker, as shown in Fig. 2. The orientation should be determined in order to avoid any contradiction between spatial and functional relationships among adjoining cells and the makers that are arranged there.

Besides, it is necessary to search the appropriate configuration of marker cells with coordinative consideration of the marker sequence, which requires iterative refinements of both aspects.

3. 3 Roles and attributes of marker sequences

A chain-type mechanism system accomplishes its objectives by converting motion features or transmitting motion positions through a series of mechanism pairs from the mover to the follower.

3. 3. 1 Qualitative representation of motion functions In order to computationally design such mechanism pairs, any symbolized abstraction for representation and manipulation is indispensable as aforementioned. Furthermore, it must share the semantics with the abstraction for spatial arrangement representation with markers and cells, as shown in Fig. 2.

We introduce the following categories of qualitative function feature indexes for representing the conceptual meanings(5) of mechanism pairs and their functional roles in an entire chain.

Direction ··· A feature index indicating kind of motion, such as rotational motion, translational motion, etc.

Mode ··· A feature index indicating mode of motion, such 'continuous one-directional' motion, 'continuous back-and-forth' motion and 'mode transforming type' motion, which aims at transforming motion posture or location, etc.

Timing ··· A feature index indicating whether an element of the pair can control the motion timing of another element or not.

Range ··· A feature index indicating movement distance by which a mechanism element is transferred. While this feature is originally quantitative, we use here another qualitative representation of 'large,' 'medium,' or 'small' under any appropriate landmark values. This qualitative representation is necessary to cooperate with the other three feature categories described in the above.

3. 3. 2 Mechanism pairs as function transformers and their sequencing Under the representation with qualitative function feature indexes, for instance, when the movement range of the mover, i.e., the input, is denoted as 'large' and one of the follower, i.e., the output, is denoted as 'small,' the functional requirement on the movement range of an entire mechanism system is denoted as 'reduce.' Against this denotation of requirements, various mechanism pairs such as gear-pair, cam, rack-and-pinion are recognized as the

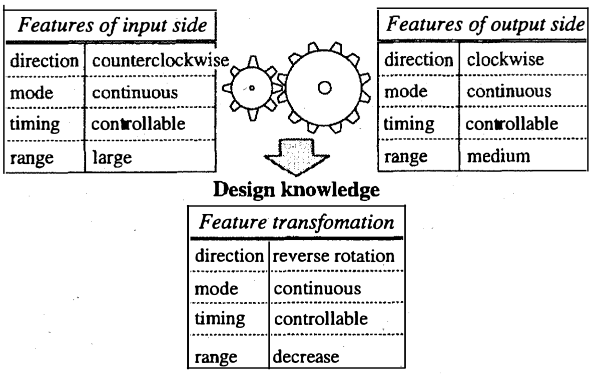


Fig. 3 Qualitative representation of a gear pair

primitives that can be used for transforming functions toward materializing overall functions. Therefore, each *mechanism primitive* can be characterized by a set of function feature indexes when recognizing it as a *function transformer* by neglecting various detailed and subsidiary attributes from the corresponding mechanism pair.

Figure 3 shows an example of such function transformers with the case of a gear pair. The upper side of the figure shows the abstraction of respective mechanism elements at input and output sides of the pair. The lower side shows the abstraction of the mechanism pair that can be deducted as their differences in function feature indexes.

Under the above abstraction concept, the design problem of the functional structure of a mechanism system is formulated as a search problem for a sequence of function transformers, the integrated transformation of which matches with the overall functional requirements of a system. That is, it can be recognized as a problem to generate a marker sequence by combining marker pairs, and can be formulated as a combinatorial synthetic problem under predefined primitives. Furthermore, it can be recognized as a search problem under the artificial intelligence paradigm. The feature transformation patterns of specific mechanism pairs, an example of which is shown in the lower part of Fig. 3, are design knowledge for selecting individual primitives toward an overall goal. Such patterns will be stored in a knowledge base in the implementation of a prototype CAD system.

3.4 Design coupling between functions and arrangement

The mutual coupling discussed in the previous section is more clearly understood under the above abstraction and formation. That is, under the viewpoint of functional requirements, any sequence with fewer markers that match with design conditions is preferable in terms of total optimality. Such a sequence is generated with higher priority in the search procedure. However, while any generated marker sequence might be able to be arranged within the entire space, whether it can be fit with the number of cells, the orientation of markers, etc. become examinable only after its markers are assigned to cells. As this scenario illustrates, either functional structure or spatial arrangement becomes examinable only after the other is tentatively assumed. Thus, it is clear that the two aspects are mutually coupled.

4. Configuration Synthesis Method for Chain-Type Mechanisms

In this section, we show the configuration synthesis method for chain-type mechanisms by using motion markers and planar cells introduced in the previous section.

4.1 Generation of marker sequence

A marker sequence is generated by searching a chain of mechanism pairs that satisfy the feature indexes of required motion transformation between the input element and the output element under the qualitativere presentation of functional requirements and mechanism pairs. That is, under the required function feature indexes that are represented qualitatively, individual mechanism elements that partially meet with particular items of requirements respectively are retrieved one by one from the input side to the output side, and then the retrieved elements are sequentially added to the tail of the tentatively assumed partial sequence. This procedure finally generates some candidates that meet the overall requirements.

The above problem is a tree search problem with multiple goals. The breadth-first search algorithm is used to solve it, because candidates with fewer mechanism elements are preferable toward achieving the global optimality of a mechanism system. Furthermore, since any candidate for marker sequence generated in this phase is tentative until its assignment to planar cells is confirmed, for instance, since there is a case where the assignment of a marker sequence fails later, a certain number of candidates are listed by the search procedure within a limited search depth and the number of mechanism elements, and they are stored for later phases through backtracking. Beyond this procedure, if any appropriate mechanism element cannot be found for any particular item of the functional requirements, it may be necessary to modify the functional requirements themselves for instance, by adding any vain elements to the sequence in order to proceed with the search operation.

4.2 Assignment of markers to arrangement space

Spatial configuration is arranged by representing the entire space with a set of planarly divided rectangular cells and then assigning the individual motion markers included in the assumed sequence to each of them. This problem is formulated as a search problem of the mapping between markers and cells(3) subject to the spatial constraints that are deducted from the necessary conditions for mechanism elements and pairs.

The overall assignment is performed through the iteration of manipulation of cells, marker arrangement to cells and determination of marker orientation.

4.2.1 Manipulation of cells In the manipulation of cells, first a set of rectangular cells is provided by the space partitioning method that divides the entire space into rectangles based on the edges of the entire space and the obstacles within it. Such a partitioning method was used in the pipe routing algorithm for an energy plant design(4). Second, they are adjusted into a set of cells of appropriate size and shape, where markers will be arranged, through merging of some cells into a single cell or further dividing individual cells into smaller cells by considering the relationships between a target candidate for marker sequence and a tentatively assumed set of cells.

Besides, the configuration of individual cells and their adjoining relationships are fairly essential to find a feasible or superior result in the succeeding operations for marker arrangement and orientation determination. Therefore, it is necessary to iterate the above operations and the following operations in order to simultaneously consider both individual issues and their relationships across different subsystems and disciplines.

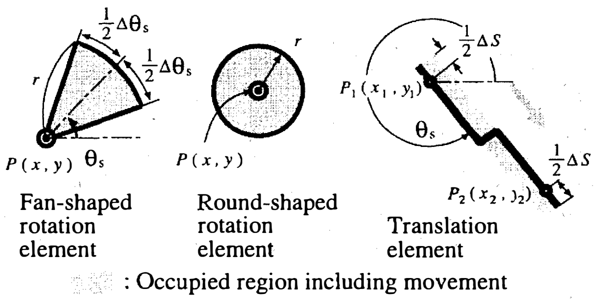
4.2.2 Arrangement of markers The arrangement of markers within a set of cells, i.e., the assignment of each marker to any cell within prepared ones, is determined one by one in accordance with the order of the marker sequence. This is also a search problem under the constraints of the neighboring relationships among markers and cells. This process is required to cooperate with the refinement of cells through their merging or division under the aforementioned mutual coupling as well.

4.2.3 Determination of marker orientation The orientation of markers that are assigned to specific cells is also determined by searching one by one. This search problem is under the constraints of functional continuity among motion markers within the sequence and the ones caused by the neighboring directions between adjoining cells. Similar to the above operations, there are some cases where it is recognized that the assumed marker sequence or cell partitioning is not suitable at this phase. In such cases, the design phase must be backtracked to the previous phases to refine cell configuration or re-execute the configuration design of the functional structure.

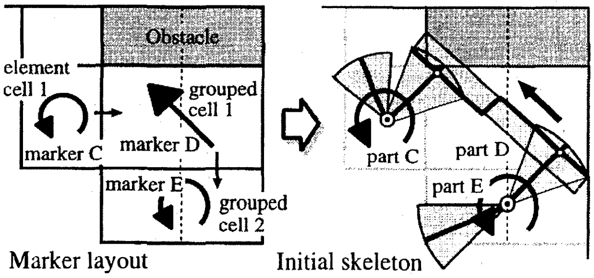
4.3 Embodiment of mechanisms from marker-and-cell representation

While the abstracted representation with markers and cells is effective for generating the conceptual configuration of a system, there are some essential design conditions that cannot be evaluated through such qualitative representation. Embodied representation with precise positions and dimensions of mechanism elements is indispensable to evaluate and criticize such conditions. Thus, such geometric information must be determined under the constraints that are deducted from a configuration design result. The configuration-based geometric modeling method(1),(2),(6) is applicable for this purpose. The method first translates the contextual meaning of geometric features to design variables, mathematical constraints and objective functions, and then determines quantitative geometric information through numerical optimization computation.

Figure 4 conceptually illustrates the procedural contents of such embodiment operation. First,



(a) Skeleton elements



(b) Translation of markers to skeletons

Fig. 4 Skeleton model for embodying arrangement geometric primitives are introduced based on respective mechanism elements, as shown in Fig. 4(a). Each geometric primitive is here a sort of skeletonized templates that includes not only original shape but also tracking shape. Then, design variables are taken from the position of joints and the dimensions of mechanism elements. The conditions for the functional relationships between adjoining mechanism elements, the elimination conditions for interferences among primitives, and so forth, are formulated as constraints in the form of equalities and inequalities. The objective function is formed toward optimality, such as the compactness of mechanism elements. Finally, any mathematical programming technique for constrained nonlinear optimization problems is applied to fix the numerical values of the introduced design variables. Figure 4(b) shows how the skeletonized geometric templates are introduced to a part of the mechanism system that is shown in Fig. 1 (a).

5. Configuration Synthesis CAD System for Chain-Type Mechanisms

5.1 Overall procedure for mechanism configuration synthesis

Figure 5 shows the overall procedure for mechanism configuration synthesis with the abstracted representation schemes and design procedures described in the previous sections. The operations for functional structure are shown on the left-hand side of the figure, and those for spatial arrangement are shown on the right-hand side. Both sides are linked to each other for the coordination of mutual coupling. That is, the procedure unfolds as follows: first, a marker sequence is assumed step by step based on motion feature indexes that are given as design requirements for the mover and the follower by using knowledge processing and artificial intelligence search techniques. Second, after the arrangement space is partitioned into a set of cells, the markers are assigned to the assumed cells. These operations are also implemented by using artificial intelligence techniques. If spatial assignment fails, space partitioning is refined through cell merging or division, or the procedure is switched to the functional structure side in order to refine the marker sequence or to switch the tentative solution to another candidate. This iteration between both sides is organized to finally reach a satisfactory design result of mechanism configuration. Subsequently, precise arrangement of the entire system and detailed geometry of the mechanism elements are embodied under a designed configuration by numerical optimization.

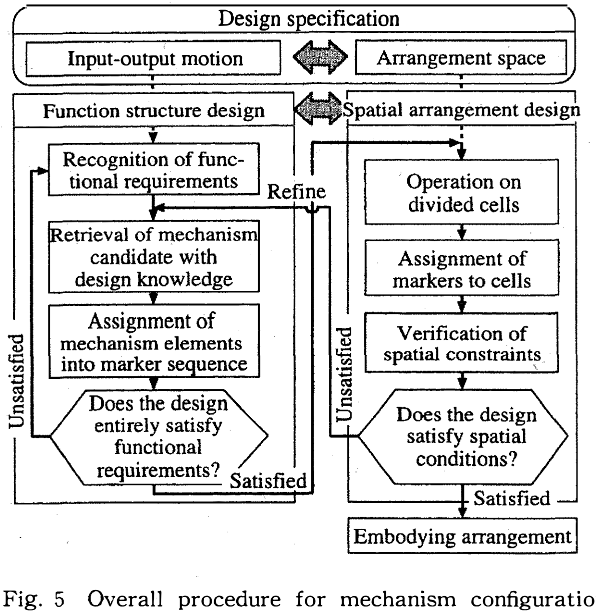


Fig. 5 Overall procedure for mechanism configuration synthesis

5.2 Interaction with a designer in synthesis process

The above procedure includes various judgments at several stages, such as in selecting a tentative solution from candidates, and in switching the design procedure across both sides. They deeply relate to what is called the mutual coupling and consequent recursive alternativeness. In other words, while the design of the functional structure cannot be finalized into a unique solution toward spatial arrangement, that is, several alternative candidates remain for the next phase, the design of the spatial arrangement natively explores more alternatives under such multiple solution candidates. This recursive generation of design candidates leads to combinatorial explosion. The spread of alternatives is rather open-ended under mutual coupling compared with conventional combinatorial search problems. Therefore, it is indispensable to prune meaningless candidates from the search tree somehow by using design knowledge. If complete design automation were sought in the implementation of computational design, design knowledge for such tree pruning would be rationally articulated for the elimination of vagueness. This is a significant topic for future design research.

Since we aim to discuss the necessity of appropriate representation media for conceptual or configurational design process and to reveal the role of mutual coupling circumstances in such process, computer implementation of the discussed outcomes cannot reach such design automation. Thus, we develop a prototype CAD system that interacts markedly with a designer who tacitly plays the role of tree pruning knowledge under combinatorial explosion. In the implementation, the computer system provides a list of prioritized promising candidates, and the designer selects a tentative design solution at individual design phases and controls any backtrack to prior design phases in order to shift the focus to another candidate that was stored beforehand.

5.3 Implementation of prototype CAD system

Practical implementation of the prototype CAD system employs the Common Lisp Object System (CLOS)(7), which is an object-oriented extension of Common Lisp, since it has superiority in terms of knowledge processing, search algorithm, and complicated object modeling due to symbolic computation ability and object orientation. A graphical user interface is developed with CLIM (Common Lisp Interface Manager) to help a designer who may play the critical role discussed above. Numerical optimization computation for mechanism embodiment is executed in the C language through process communication with the subsystem implemented in Lisp.

6. Design Applications

We demonstrate the design applications of the implemented prototype CAD system for configuration synthesis problems of mechanism systems.

6.1 Synthesis of mechanisms used in a video-cassette recorder

First, the prototype CAD system is applied to the design problem of partial mechanisms used in a video-cassette recorder (VCR). Table 1 shows the description of design requirements with qualitative function feature indexes. Figure 6 shows the spatial conditions for the entire space shape and the locations of a mover and three followers. The target system includes two subsystems: the tape loading mechanism that drives two pins for winding up a video tape to the recording and playback head, and the pinch-roller pressing mechanism that presses a video tape to the pinch roller for tape traveling. These two subsystems share rotational motion at the motor shaft as their input.

Figure 7(a)-(e) show the design process of the tape loading mechanism, where sliding motions of two arms are designed as output motions. Figure 7(a) illustrates a marker sequence as the functional structure, which still includes some markers without orientation. Figure 7(b) shows the consequent assignment of some markers that transmit motion from the motor shaft to the loading pin at the right-hand side. Through this phase, it becomes possible to evaluate motion connectability among mechanism elements for the determination of marker orientation. Figure 7(c) is the design result of such orientation. Figure 7(d) shows the final assignment result of all markers in the sequence defined in Fig. 7(a), where motion is branched at a gear and then transmitted to the other loading pin at the left-hand side. This phase fixes the configuration of two tape loading mechanisms. Figure 7(e) shows the consequent embodiment result of spatial arrangement and geometric skeletons of all mechanism elements from the configuration shown in Fig. 7(d). Figure 7(f) shows the overall design result that includes the pinch-roller pressing mechanism. This result is almost equivalent to an existing design for an actual product.

Table 1 Required functions of VCR mechanism

Feature	Input	Output		
		TL-A	TL-B	PR
direction	counter-clockwise	+Y trans.	+Y trans.	counter-clockwise
mode	mode trans.	mode trans.	mode trans.	mode trans.
timing	—	controllable	controllable	controllable
range	large	medium	medium	small

TL-A, B: tape loading mechanisms A and B
PR: pinch-roller pressing mechanism

Besides, an alternative design that generates simultaneous motion of two pins with a slider-crank mechanism rather than gear-pairs, as shown in Fig. 8, is also generated in the process that finally reaches the design result shown in Fig. 7(e). However, this alternative design has some disadvantages. The mechanism system does not fit into the entire space at the left-hand side crank. Furthermore, it is difficult to ensure synchronized motion between both pins of the tape loading mechanisms. Given this tentative situation, the designer judges that it is effective to increase shared mechanism elements between two subsystems for tape loading in order to avoid the latter disadvantage, and then decides to shift the branch point to the left-side area. The design result shown in Fig. 7(f) is finally generated by backtracking to a corresponding step of the design process from the situation of Fig. 8 and then exploring another alternative design that can overcome such disadvantages.

The reason why the design process is unstably deployed as shown in the above is that its process flow

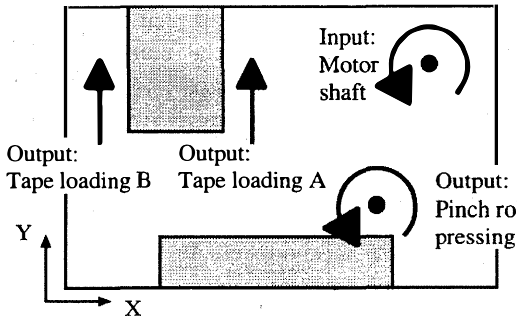
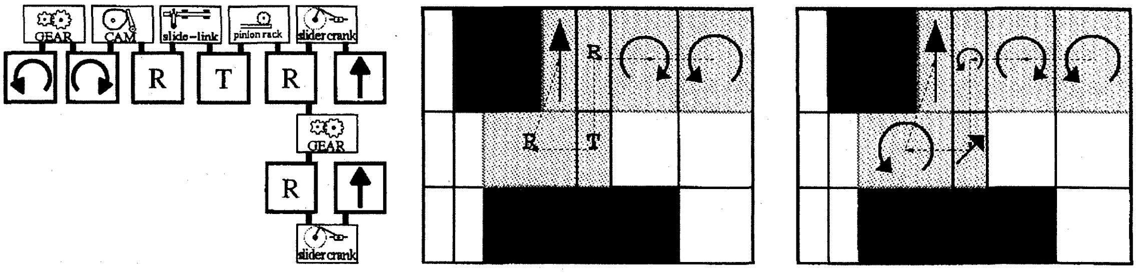


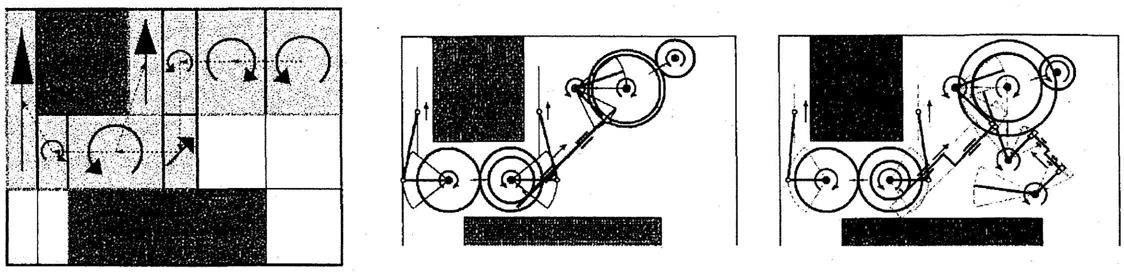
Fig. 6 Spatial design conditions of VCR mechanism



(a) Marker sequence with undirected markers

(b) Marker layout with undirected ones

(c) Determination of marker directions



(d) Mechanism layout configuration

(e) Embodied skeleton model of tape loading mechanism

(f) Design result of the overall system

Fig. 7 Application to tape loading mechanism and pinch-roller mechanism

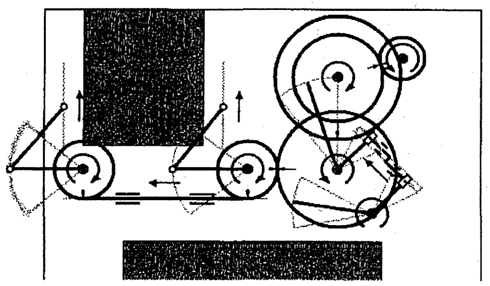


Fig. 8 An alternative design of the overall system

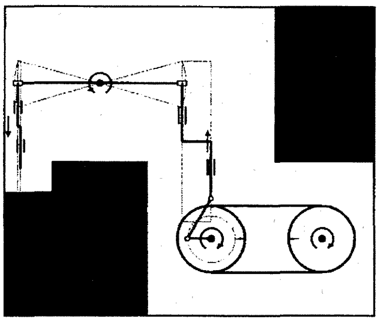


Fig. 9 Application to motor press mechanism

depends strongly on the judgment of the designer, as aforementioned. It indicates that the developed synthesis method and the implemented prototype CAD system are insufficient as a fully automated design computation. However, what the designer does is to passively select a tentative solution from proposed prioritized candidates at respective steps. This fact and the obtained design results of Figs. 7 and 8 demonstrate the validity and rationality of the abstracted representation schemes and the consequent design procedure proposed in this paper as the bases for sophisticated computational design support systems.

6.2 Synthesis of motor press mechanism

Following the application to a VCR design example, Fig. 9 shows an application to the design problem of a motor press mechanism. In this example, the marker sequence is generated to transmit motion from motor rotation at the right-bottom area to translatively pressing motion at the left-middle area by avoiding a non-allowable region, and then the mechanism system is embodied as shown in the figure.

Other than the above two examples, the developed method and system have been applied to mechanisms for piston-crank-type internal combustion engines, etc.

7. Related Studies and Discussion

We compare here this study with other studies on mechanism synthesis and then discuss the relationships of computational approaches in design engineering and other fields.

Since mechanisms are important elements for mechanical systems, their design problem has been investigated from various viewpoints. For instance, Hoeltzel and Chieng(8) developed an approach to find and optimize the configuration and geometry of multibar linkages behaving along a given motion path.

Gupta and Jakiela(9) proposed a method for synthesizing the shapes of mechanism elements. Murakami and Nakajima(10) and Subramanian and Wang(11) studied algorithms to retrieve an appropriate or feasible mechanism pair from existing ones and to configure their combination for given design conditions, respectively. However, their outcomes remain in the restricted levels of mechanism synthesis, as they can deal with only simple mechanism pairs rather than mechanism systems. Apart from them, Kota(12) proposed a design method of mechanism systems with function decomposition through matrix representation. It is remarkable that his viewpoint was applied to systematic functions.

In comparison with the above studies, our viewpoint is to focus on both systematic structure for a series of mechanism elements and its mutual coupling with spatial arrangement. As aforementioned, when considering the design problem of a system as a whole, it is indispensable to consider the diversity of disciplines and granularity levels. Representation and manipulation of geometry have been a major subject in various kinds of engineering problems, and state-of-the-art techniques for geometric modeling have become significant tools for detail design phase or mechanical parts design. Conceptual design or configurational design does not deal with such detailed precise representation of geometry, rather it prepares some prerequisites for such contents. Furthermore, it is pointed out that the manipulation of such prerequisites requires any qualitative representation in order to focus on the global situation of an entire system. After the success of qualitative reasoning in the conceptual modeling of physical behavior, *diagrammatic reasoning*(13),(14) has been proposed as a reasoning method for the qualitative aspect of geometric information in the field of artificial intelligence. In another direction, one aspect of the difficulty in conceptual design can be explained by combinatorial conformity among system elements to realize an integrated system behavior. For instance, Pugh's method(15) indicates that a conceptual design result must be piled up from partial combinations to an overall combination since the possibilities of combinations are so large.

The configuration synthesis method proposed here can be characterized as follows given the above situations. The abstracted representation with markers and cells can be recognized as an implementation of diagrammatic reasoning for mechanism systems design. This implementation enables piling up of mechanism pairs to a mechanism system. In other words, fictitious representation media facilitate the formulation of the early phases of a design process and the implementation of a computational design method that has certain functionality. The generalized meaning of these research results is that the introduction of any fictitious representation media is essential toward computerization of the early phases of a design process, and that it is indispensable to make the contents of design processing operational under a particular formalism.

Another characteristic of the configuration synthesis method proposed in this paper is the resolution of mutual coupling between functional structure and spatial arrangement through piling up of partial tentative design solutions. In the implementation of a prototype CAD system, the control of such a resolution depends strongly on the designer's judgment, since recursive piling up of alternatives across both aspects leads to open-ended combinatorial explosion. However, the structurization of design procedures with recursive dependence between both aspects can explain how mechanism systems design is explored, even though it is essentially a result of the designer's judgment. The interpretation of this hidden fact is that partial tentative solutions act as *situations* for succeeding design operations, and their role is significant. It must be confirmed if this meaning of situations can be generalized for other classes of conceptual design and configurational design of mechanical systems as well.

8. Concluding Remarks

We proposed herein a configuration synthesis method of mechanism systems by introducing abstracted representation with motion markers and planar cells, and implemented a prototype CAD system based on it. Its application to several design problems proved its validity and promise. Generalization of its outcome indicates the essential role of fictitious abstraction and consequent formalization of design computerization in the early phases of a design process. Furthermore, it implies the role of situations in the overall design of complicated systems. We plan to refine the representation of spatial information, the processing method of mutual coupling structure and so forth as our future work.

This research was partially supported by Ministry of Education, Science, Sports and Culture of Japan through a Grant-in-Aid for General Scientific Research 10650144 and the "Research for the Future" Program of the Japan Society for the Promotion of Science (JSPS) under "Methodology for Emergent Synthesis" Project (project number 96P00702).

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