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**Short Paper**

# A DECOMPOSITION METHODOLOGY FOR DESIGN OF MECHANISMS FROM FUNCTIONAL AND STRUCTURAL PERSPECTIVES

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## ABSTRACT

This paper presents an innovative methodology for the design of mechanisms. The course of design is decomposed functionally and structurally into two portions as the design of two mechanism modules: the functioning module and the constraining module. Conceptual functions of mechanisms are embodied as the functional requirements to construct admissible functioning modules. Following that, the functioning module is then assigned into feasible kinematic structures existing in the graph atlas to yield admissible structures for the mechanism. Finally, remaining characteristics featured by the constraining module are determined according to the structural requirements of the mechanism. By this methodology, both functional and structural requirements are concurrently taken into account during the design process, to obtain feasible mechanisms without an exhaustive enumeration process. The design of mechanisms can thus be performed in an effective and systematic manner.

***Key Words:*** mechanism design, kinematic structure.

## I. INTRODUCTION

In the process of mechanism design, the most difficult part is often the conceptual design phase, the creation of a mechanism to achieve specific functions. As a whole, the design of a mechanism is the fruit of designers' ingenuity, intuition and experience. However, in recent decades, the application of graph theory has been a major breakthrough in the pursuit of a systematic approach to mechanism design and analysis, and the most significant of all is the representation of a mechanism's kinematic structure with graphs. From that point on, the mechanism design was able to evolve in a relatively more systematic manner (Buchsbaum and Freudenstein, 1970; Crossly, 1965; Davies, 1968; Dobrjanskyj and Freudenstein, 1967; Freudenstein, 1971; Freudenstein and Dobrjanskyj, 1965; Woo, 1967). Freudenstein and Maki (1979) first proposed the concept of separating the kinematic structure from its function. With this concept, kinematic structures with desired complexity are fully enumerated impartially for a complete search of potential mechanisms. Evaluation of each obtained structure can then take place with respect to the functional requirements, while screening out the unqualified candidates. The concept has been applied to mechanism design in a variety of industrial applications (Datseris and Palm, 1985; Erdman and Bowen, 1981; Freudenstein and Maki, 1983; Freudenstein and Maki, 1984; Yan, 1992). However, precisely because the consideration of functional requirements is merely involved during the enumeration stage, numerous functionally infeasible kinematic structures are subsumed. Hence, inability to avoid infeasible results becomes a complex problem that greatly diminishes design efficiency.

In this paper, the development of a modular methodology for the design of mechanisms offers a

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more effective solution. It will be shown that a mechanism consists of two modules: the functioning module and the constraining module. The course of design is then decomposed functionally and structurally into two portions. From the functional perspective, conceptual functions of the mechanism are embodied as the functional requirements. They are realized by settling the joint specifications in the functioning module and are used to construct admissible functioning modules accordingly. Therefore, the functions of the mechanism can be fully taken into account at the beginning of the design process. From the structural perspective, feasible kinematic structures are searched from the existing graph atlas by applying the structural requirements. Then the process further evaluates the admissible structures for the mechanism by the assignment of the functioning module into feasible kinematic structures. The constraining module is determined at the last stage, to complete the design of the mechanism. This methodology integrates the functional and structural requirements into the design process in an effective and systematic manner. The example of the design of a latch mechanism for a wafer transport container can illustrate the method at work in detail.

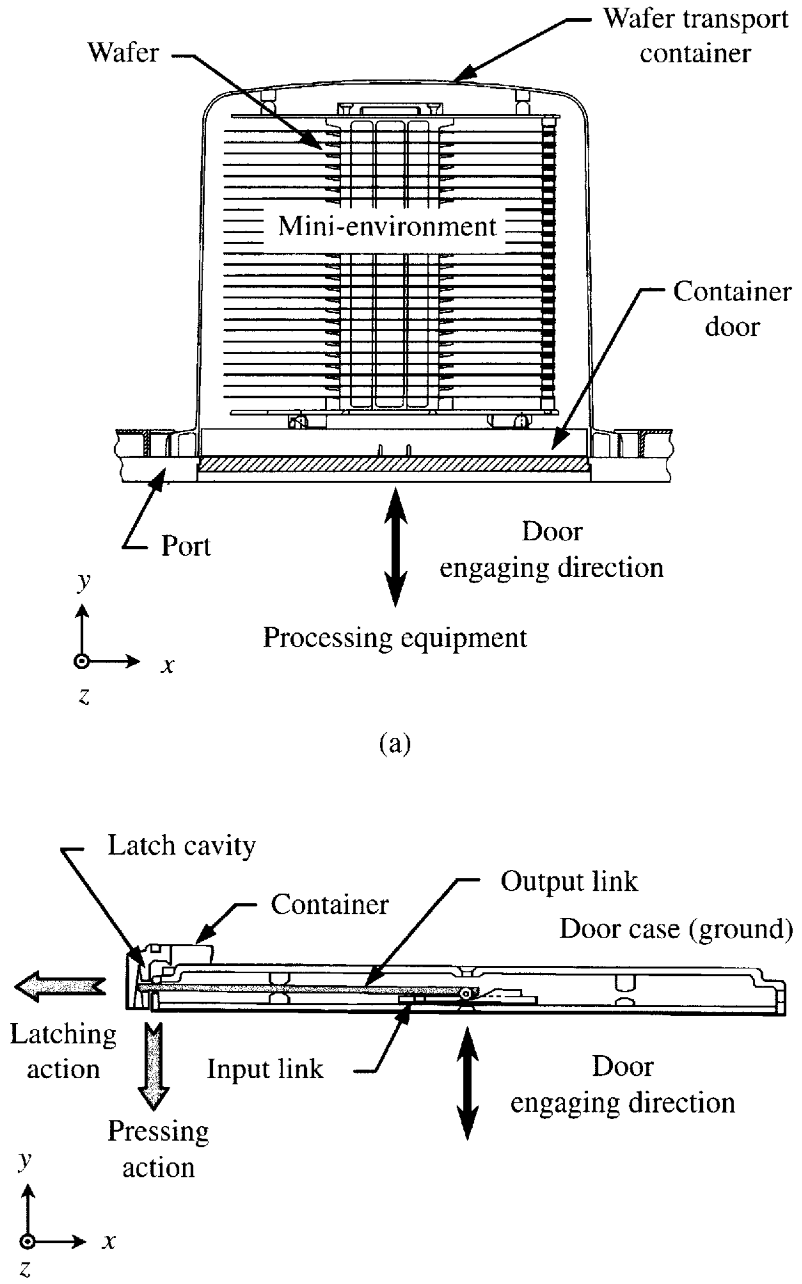
## II. EMBODIMENT OF FUNCTIONAL REQUIREMENTS

The decomposition methodology first embodies the general conception of functions to generate functional requirements for the mechanism. Issues such as which link and what kinds of motion are required to achieve the functions of the mechanism are specifically clarified at this stage. Usually, the achievement of functions is connected to the motions of certain links. These links consisting of the input link, output link and ground link are designated as the key links. Consequently, the functional requirements are represented as:

a. Motion type of the key link, such as rotary motion, linear motion, etc.
b. Operating direction of the key link.

A kinematic chain consisting of key links can be constructed through determining the adjacency relations between the key links. This key-link chain is defined as the functioning module of the mechanism. The motion type and operating direction of the key link can be yielded by the joint specifications in the module, including the type and orientation of joint. As a result, the evaluation of functions can be administered in the conceptual design process.

To illustrate the methodology, the design of a latch mechanism for a wafer transport container is used as an example. As Fig. 1(a) shows, the standard mechanical interface (SMIF) environment provides one approach to interfacing a clean wafer transport container to the port on semiconductor processing equipment. The wafer transport container creates a particle-free and airtight mini-environment to prevent wafers from contamination by abrading particles during transportation or storage. As shown in Fig. 1(b), the latch mechanism in the container door works to latch the door and to improve the air-tightness of the mini-environment by the motion of the output link with respect to the ground link (door case).



(a)

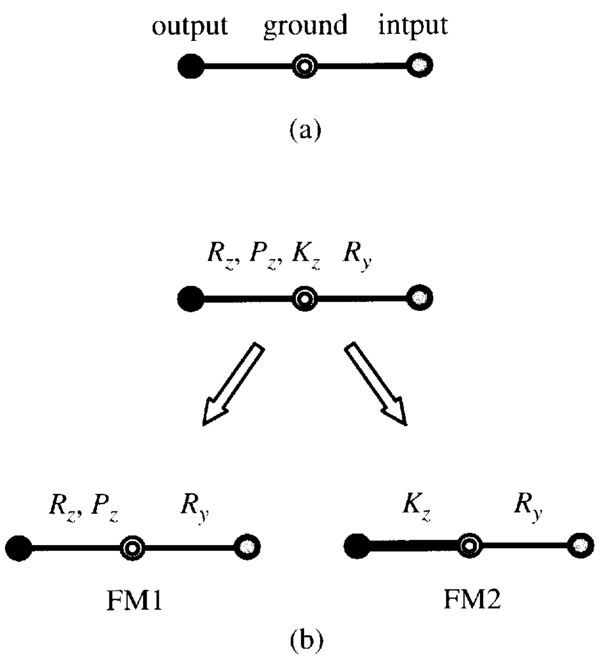
(b)

Fig. 1 (a) SMIF environment; (b) Latch mechanism

As Fig. 1(b) indicates, the motion of output link is required to comprise the displacement perpendicular to the engaging direction of the container door to effect the latching of the container. The motion of output also has to comprise the displacement along the door engaging direction to press the latch cavity rim. This results in an airtight sealing effect of the container. Based on these interfacing conditions, the functional requirement of the output link is specifically clarified as follows, assuming the engaging direction of the container door is oriented in direction $y$:

***R1:*** *The output link must produce a motion that comprises displacement in direction x and in direction y with respect to the ground link.*

To drive the latch mechanism, the SEMI



(a)

(b)

Fig. 2 (a) Key-link chain of the latch mechanism; (b) Admissible functioning modules

standards (Book of SEMI standards) provide the means of rotating the input link about the $y$-axis for 200 mm and 300 mm SMIF environments. The functional requirement of the input link is specifically clarified as follows.

***R2:*** *The input link must produce a rotary motion about the y-axis with respect to ground link.*

To better facilitate the required motions, the output and input links are set adjacent to the ground link. Accordingly, the functioning module of the latch mechanism can be constructed in the form of the key-link chain as shown in Fig. 2(a). In the graph representation (Buchsbaum and Freudenstein, 1970), links are denoted by vertices and joints by edges. As presented in Fig. 2(a), the output link is denoted by a solid vertex, the input link by a gray vertex and the ground link by double circles. The joint between the output and ground links is called the output joint, while the joint between the input and ground links is called the input joint.

## III. CONSTRUCTION OF ADMISSIBLE FUNCTIONING MODULES

The motion type and operating direction of the key link can be realized by the assignment of the joint specifications of the key-link chain. The required motion type can be obtained through labeling the corresponding type of joint. For instance, rotary motions can be produced by revolute joints and linear motions can be produced by prismatic joints. The required operating direction of the key link can be achieved through appropriately arranging the orientation of the joint. There may be several choices for each joint specification to fulfill those requirements. Admissible functioning modules are then constructed through combining these joint specifications.

For the illustrated example, the latch mechanism is designated as a planar mechanism. It is clear that the actions of the output link relative to the ground link are determined according to the output joint. As seen in ***R1***, the latching and pressing actions are achieved by directing the output link to move on the $xy$ plane that contains the latching direction $x$ and the pressing direction $y$. A revolute joint, prismatic joint and planar cam pair are used in this example. Define the orientation axis of the joint as the axis perpendicular to the motion plane generated by two paired links. Then, the required $xy$ plane motion can be attained through allocating the orientation axis of the output joint along the $z$-axis. Thus, the first functional characteristic is concluded as follows:

***C1:*** *The output joint can be designated as a revolute joint (R) or prismatic joint (P) or planar cam pair (K), with the orientation axis allocated along the z-axis.*

As for functional requirement ***R2***, the required rotary motion about the $y$-axis for the input link can be achieved by designating the input joint as the revolute joint with the orientation axis about the $y$-axis. Thus, another functional characteristic is concluded as follows:

***C2:*** *The input joint can be designated as a revolute joint (R) with the orientation axis allocated along the y-axis.*

The ***C1*** and ***C2*** yield feasible designs for the output and input joints to obtain admissible functioning modules. The result is shown in Fig. 2(b) where the input and output joints are labeled according to joint type with the suffix indicating the orientation axis. Admissible functioning modules are classified into two categories: one as FM1, containing a 1-DOF output joint, $R_z$ or $P_z$, labeled as a thin edge, and another as FM2, containing a 2-DOF output joint, $K_z$, labeled as a heavy edge.

## IV. SEARCH OF FEASIBLE KINEMATIC STRUCTURES

In this phase, feasible kinematic structures for assigning the admissible functioning modules are searched according to the structural requirements of the mechanism. To determine the kinematic structure of the mechanism, the first step is to find its numbers of links and joints. These numbers must follow the general degree-of-freedom (DOF) equations:

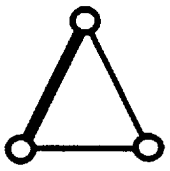
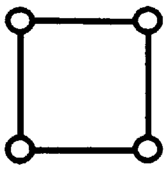
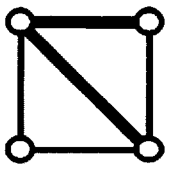
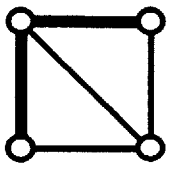
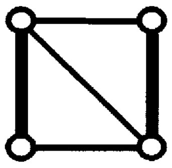
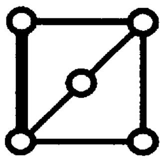
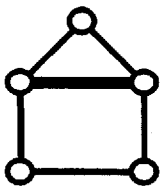
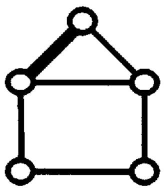
$$F = \lambda \cdot (n-1) - \sum_{i=1}^{\lambda-1} (\lambda-1) \cdot j_i \tag{1}$$

and

$$j = \sum j_i \tag{2}$$

where $\lambda$=3 for planar mechanisms, $\lambda$=6 for spatial mechanisms, $F$ denotes the DOF of the mechanism, $n$ the number of links, $j_i$ the number of $i$-DOF joints

**Table 1 Admissible graphs for 1-DOF planar mechanisms with up to 5 links**

| $n$ | $j_1$ | $j_2$ | $(n, j)$ | Admissible Graphs | | |
|---|---|---|---|---|---|---|
| 3 | 2 | 1 | (3, 3) |  | | |
| 4 | 4 | 0 | (4, 4) |  | | |
| | 3 | 2 | (4, 5) |  |  *<br>No. 1 |  *<br>No. 2 |
| 5 | 5 | 1 | (5, 6) |  |  |  *<br>No. 3 |

Asterisk: feasible graphs for the functioning module

and $j$ the number of joints.

For a given DOF of mechanism $F$ and number of links $n$, corresponding number of joints $j$ can be obtained by solving integer $j_i$ of Eq. (1). Admissible kinematic structures with given numbers of links and joints can then be searched from the existing graph atlas (Buchsbaum and Freudenstein, 1970; Mayourian and Freudenstein, 1984).

In the example, the latch mechanism is assumed to have 1-DOF and up to 5 links. By substituting $\lambda$=3, $n$=3 or 4 or 5, and $F$=1 into Eq. (1), integer $j_1$ and $j_2$ can be solved as shown in Table 1. Feasible numbers of links and joints $(n, j)$ are then obtained, and admissible graphs can be searched as shown in Table 1 where the lower pairs are denoted by thin edges and the higher pairs by heavy edges. For the planar mechanism, since links in the same loop of a mechanism are constrained to move on the same plane, the links of the functioning module moving on distinct $xy$ and $xz$ planes must be placed in different loops of the mechanism. The common link connecting two loops shall move linearly along the intersection of the two different planes, and hence should be designated as a prismatic joint aligned in this intersection. Further, to avoid adjacent prismatic joints in the same direction, only one common joint in a feasible graph is allowed. Thus, only multi-loops graphs with one 1-DOF common joint (prismatic joint) are feasible for this example. Feasible graphs are shown with an asterisk in Table 1.

## V. ASSIGNMENT OF FUNCTIONING MODULE INTO FEASIBLE KINEMATIC STRUCTURES

Admissible structures for the mechanism are obtained by assigning the functioning module into the feasible kinematic structures. The assignment can be executed through placing the thin edges of functioning modules corresponding with the thin edges of feasible graphs, and heavy edges corresponding with heavy edges. For a planar mechanism, the links of the functioning module moving on a single plane can be arbitrarily assigned into the same or different loops of kinematic structure, and the links moving on different planes must be assigned into different loops. As for the spatial case, the links can be assigned into arbitrary loops of the mechanism.

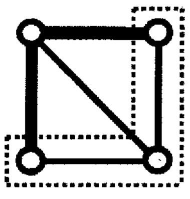
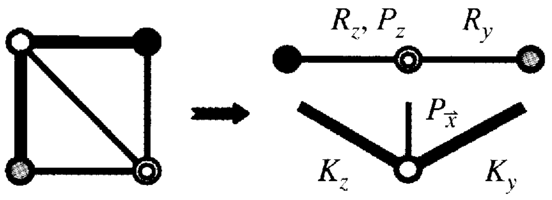
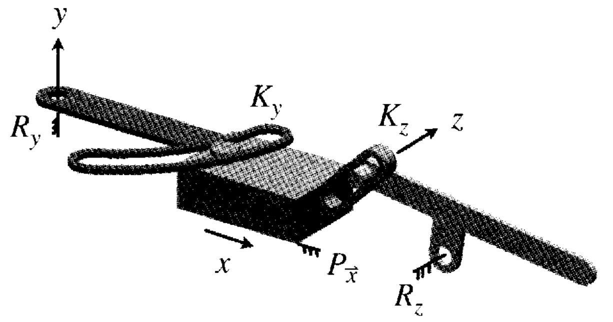
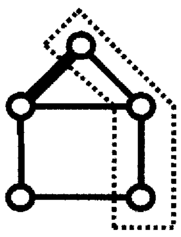
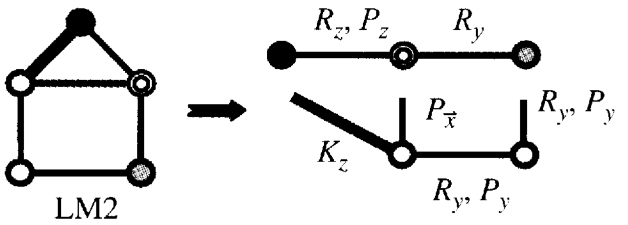
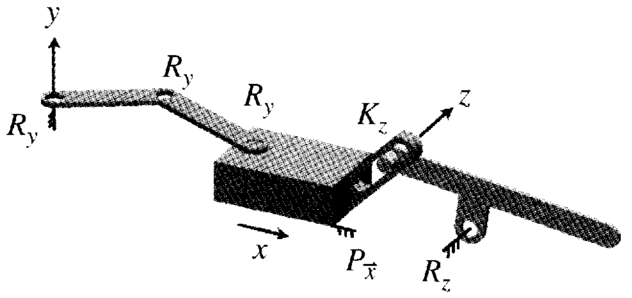
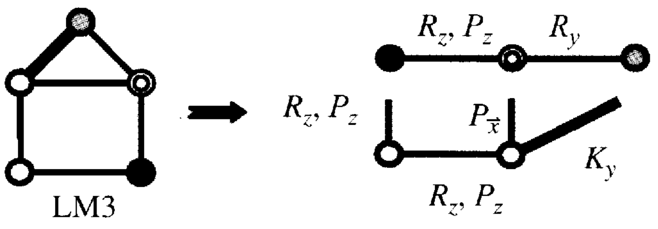
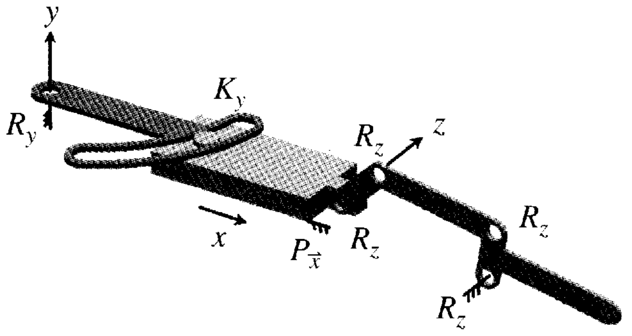
For the example discussed here, admissible functioning modules FM1 and FM2 are assigned into the three feasible graphs in Table 1. As required, the output link and input link moving on distinct planes must be assigned into two separate loops of the feasible graphs. The functioning module FM1 with two thin edges can be assigned coincident with a thin-thin edge path located in different loops of a feasible graph. The left-side column of Table 2(a) shows feasible thin-thin edge paths of the feasible graphs. The middle column of Table 2(a) shows the assignment results LM1, LM2 and LM3. Similarly, the functioning module FM2 can be assigned coincident with a thin-heavy edge path located in different loops of a feasible graph, and the results LM4 and LM5 are shown in Table 2(b).

## VI. DETERMINATION OF CONSTRAINING MODULE

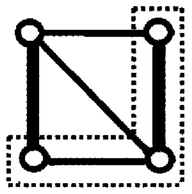
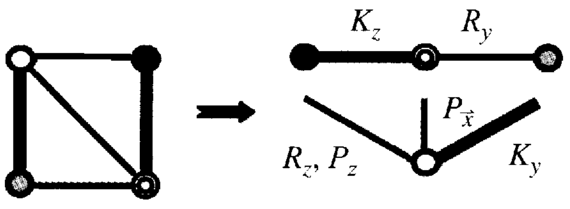
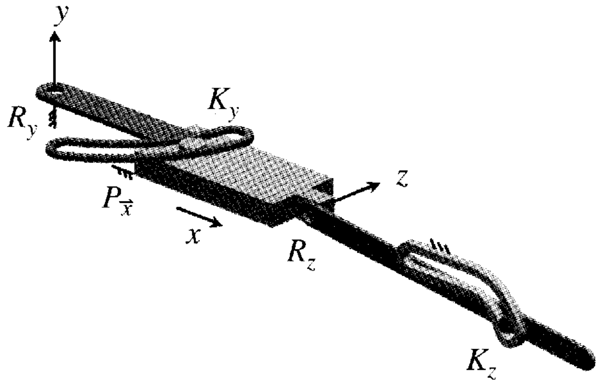
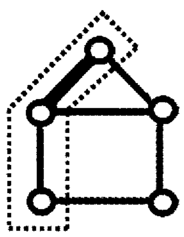
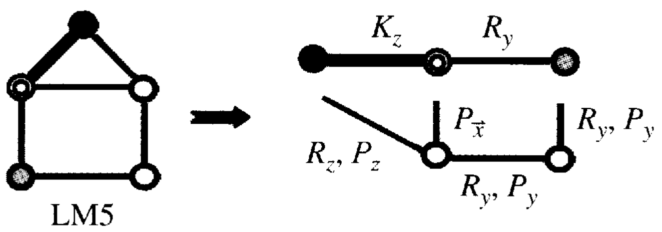
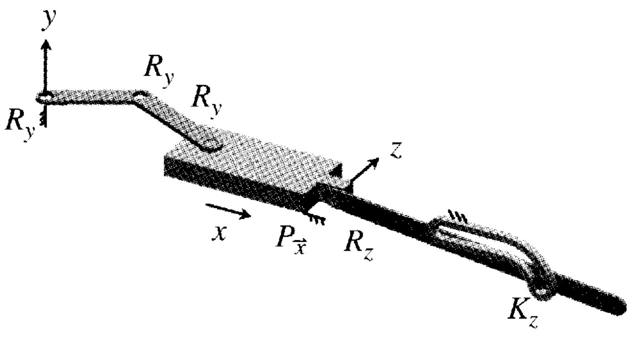
Excluding the functioning module from the admissible structures for the mechanism, the remaining links and joints are identified as the constraining module. The types of the joints in the constraining module can be determined according to the joint DOF condition, that is, revolute or prismatic joint can be assigned for the 1-DOF joint, and planar cam pair for the 2-DOF joint, etc. As for the orientation of the joint, since links in the same loop of a planar mechanism are constrained to move on the same plane, the orientation axes of joints in the same loop must point in the identical direction. Therefore, the orientation axes of the joints in the constraining module can be determined to be the same as the joint orientation axes of the functioning module in a loop. As for spatial mechanisms, the joint orientations can be arbitrarily arranged, with the exception of those resulting in

**Table 2 Planar latch mechanisms up to 5 links (a) with FM1; (b) with FM2**

(a)

| Feasible Graphs | Feasible Latch Mechanisms | Possible Functional Schematics |
|---|---|---|
| <br>No. 1 |  <br>LM1 |  |
| <br>No. 3 |  <br>LM2 |  |
| |  <br>LM3 |  |

(b)

| Feasible Graphs | Feasible Latch Mechanisms | Possible Functional Schematics |
|---|---|---|
| <br>No. 2 |  <br>LM4 |  |
| <br>No. 3 |  <br>LM5 |  |

planar mechanisms.

As the example shows, the admissible structures for the latch mechanism, LM1 to LM5 are divided into the functioning module and the constraining module as shown in Table 2. In the constraining module, the 1-DOF joints can be specified as a revolute joint ($R$) or prismatic joint ($P$), and the 2-DOF joints can be specified as a planar cam pair ($K$). Since the orientation axes of the joints in the same loop must point in the identical direction, the orientation axes of the joints in the constraining module with the output link in the same loop can be set along the $z$-axis. Similarly, the orientation axes of the joints in the constraining module with the input link in the same loop can be set along the $y$-axis. As for the common joint between the two loops, only a prismatic joint in the *x*-axis, at the intersection of *xy* and *xz* planes, can be assigned. The common joint is labeled as $P_{\vec{x}}$ with an arrowed suffix indicating the direction of motion. The middle column of Table 2 shows the assignment results of the joints in the constraining module. The right-side column of Table 2 shows possible functional schematics of LM1 to LM5 with all 1-DOF joints in the constraining module selected as revolute joints. It can be seen that the motions of links in a mechanism belong to the *xy* and the *xz* planes, and the common link moves along the intersection of the two planes, direction *x*. The output link moving on the *xy* plane can provide the latching and pressing actions.

## VII. CONCLUSION

In this paper, a modular methodology for the design of mechanisms is presented. The conceptual functions of mechanisms are embodied as functional requirements, which are brought into the design process and used noticeably for the construction of functioning modules, the search of feasible kinematic structures and the determination of a constraining module. Compared with the design method where the evaluation is performed after an exhaustive enumeration process, this methodology, emphasizing the cooperation of functional requirements with the design process, can enhance the efficiency of design. It is anticipated that this methodology can be useful for mechanism design in the conceptual design phase.

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