Research on Mechanics Symmetry Ontology

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***Abstract*—On the basis of the specific existence of symmetry in mechanical systems, its existence and functions were analyzed. Based on the above, a framework of mechanics symmetry ontology was established. The definitions and descriptions of the concepts in mechanics symmetry were presented and then the descriptions of the relationships between the elements in mechanics symmetry ontology in the definition range were proposed. Finally, its research prospect was put forward.**

***Index Terms*—symmetry, ontology, mechanics symmetry, ontology elements.**

I. Introduction

There are many kinds of specific existences of symmetry in natural phenomena and artificial systems: such as petal, snowflake and crystal in the former, and building, auto and plane in the latter. The research on symmetry was conducted in many fields, such as aesthetics[1], mathematics[2][3][4][5], biology[6][7][8], physics[9][10] and so on. Especially in physics, deep and systematic research on symmetry has been carried out, which has achieved a lot[11][12][13]. In different fields, symmetry all plays a crucial role. In biology, the development of biologic symmetry, to some extent, embodies the direction and rule of biologic evolution. In physics, symmetry theory guides the advancement of physical research, and it is an important method in the research of macroscopic and microcosmic physics[11][12][13].

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In mechanics, symmetry develops with the development of mechanical system, and symmetry exists in almost all mechanical systems. Symmetry plays an important role in mechanical system, and therefore deep and systemic research on mechanics symmetry (MS) and the establishment of its theory system can guide the design process of mechanical products, benefit innovative design, and improve the efficiency of product design. But currently systematic research on MS is still a suspending problem. Research on symmetry's application in mechanics can only be referred in Barrenscheen's dissertation (German, 1990) [14].

There are many kinds of different idiographic existences of symmetry in mechanical system, among these existences, difference as well as relationship coexists and so do the commonness and isomerism. Ontology will benefit to the exploration of research on commonness of MS. In this paper, based on the former research, referring to the platforms of biology symmetry ontology, physics symmetry ontology and common symmetry ontology [15], combining the examples of MS, a framework of MS ontology was established; this paper provides a basic platform for subsequent research on MS.

In this paper, MS is defined as follow:

Definition 1: MS means an ordered repeating of some element in a mechanical system, which describes the similar rules of this mechanical system. MS exists in four levels of a mechanical system, namely function level, principle level, structure level and process level. MS ontology is defined as $\mathbf{S_m}=<\mathbf{C_m}, \mathbf{CA_m}, \mathbf{E_m}, \mathbf{EA_m}, \mathbf{R_m}>$, where $\mathbf{C_m}$ - MS concept set, $\mathbf{CA_m}$ -MS concepts' attribute set, $\mathbf{E_m}$-MS example set, $\mathbf{EA_m}$ –MS examples' attribute set, $\mathbf{R_m}$ – MS relationship set.

II. MS Concept Set C_m

MS concept set $\mathbf{C_m}=<\mathbf{c_s}, \mathbf{c_{po}}, \mathbf{c_f}, \mathbf{c_{pi}}>$, is a hierarchical concept system, including structure symmetry $\mathbf{c_s}$, process symmetry $\mathbf{c_{po}}$, function symmetry $\mathbf{c_f}$ and principle symmetry $\mathbf{c_{pi}}$, as figure 1.

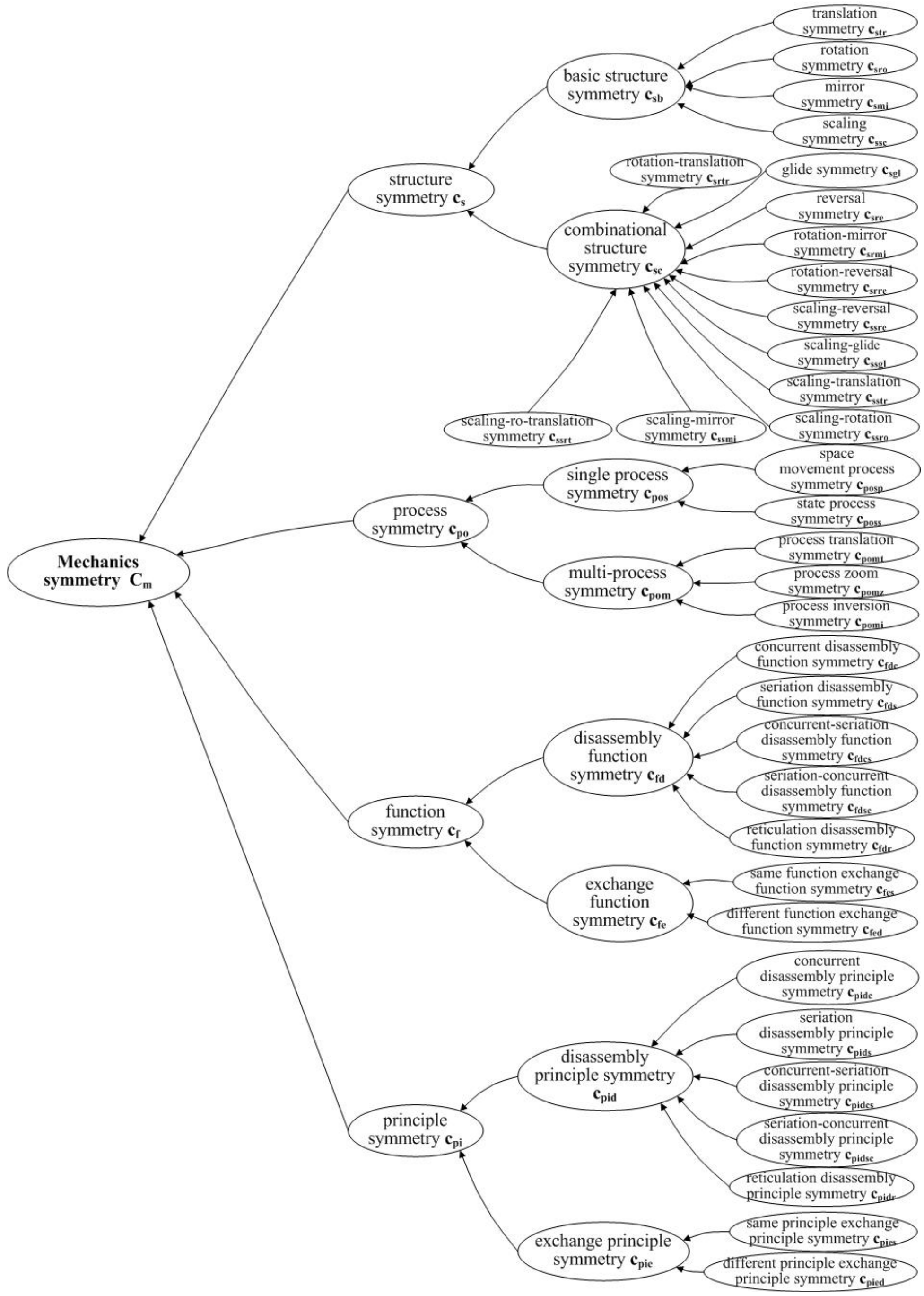

Figure 1: elements and hierarchical levels of mechanics symmetry ontology

Definition 2: If a mechanical system has two or more identical parts in geometric structure, and these parts are arranged orderly according to some rule or regulation, then the mechanical system has structure symmetry.

Structure symmetry $\mathbf{c}_s = \langle \mathbf{c}_{sb}, \mathbf{c}_{sc} \rangle$, where $\mathbf{c}_s$- basic structure symmetry $\mathbf{c}_{sb} = \langle \mathbf{c}_{str}, \mathbf{c}_{sro}, \mathbf{c}_{smi}, \mathbf{c}_{ssc} \rangle$, combination structure symmetry $\mathbf{c}_{sc} = \langle \mathbf{c}_{srtr}, \mathbf{c}_{sgl}, \mathbf{c}_{sre}, \mathbf{c}_{srmi}, \mathbf{c}_{srre}, \mathbf{c}_{sstr}, \mathbf{c}_{ssro}, \mathbf{c}_{ssmi}, \mathbf{c}_{ssgl}, \mathbf{c}_{ssre}, \mathbf{c}_{ssrt} \rangle$. Combination structure symmetry is composed of basic structure symmetries. The sketch map of structure symmetries is showed in table 1.

Figure 2 is an example having mirror symmetry, figure 3 is an example having scaling-translation symmetry.

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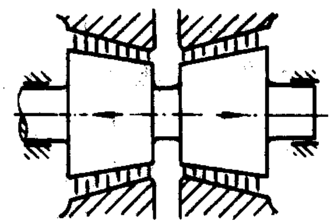


Figure 2: mirror symmetry structure[16]

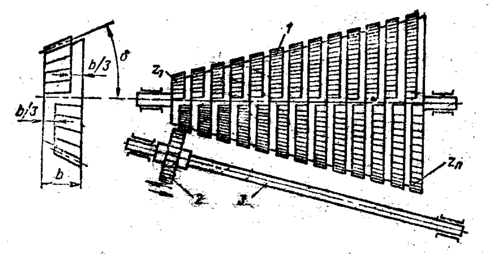
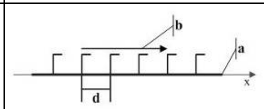
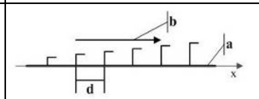
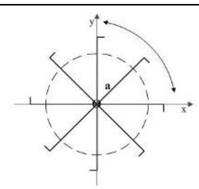
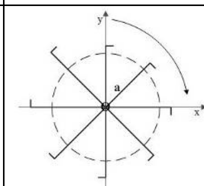
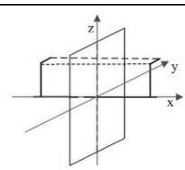
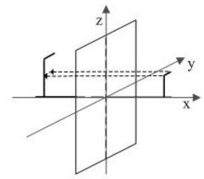
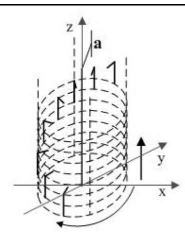
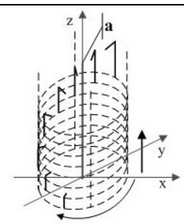
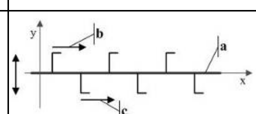
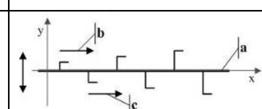
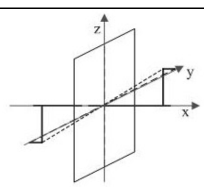
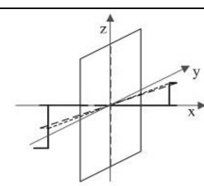


Figure 3:scaling-translation symmetry structure[18]

Table 1: sketch map of structure symmetries

symmetry	sketch map	description	symmetry	sketch map	description
translation symmetry c_{str}		Translate with equal interval d along the direction of vector b	scaling-translation symmetry c_{sstr}		the locations of symmetry elements are arranged as translation symmetry, the sizes change regularly
rotation symmetry c_{sro}		rotate along the axis vertical to rotating plane with angle a	scaling-rotation symmetry c_{ssro}		the locations of symmetry elements are arranged as rotation symmetry, the sizes change regularly
mirror symmetry c_{smi}		mirror operation can be processed in two-dimensional plane and also in three-dimensional space	scaling-mirror symmetry c_{ssmi}		the locations of symmetry elements are arranged as mirror symmetry, the sizes change regualrly
rotation-translation symmetry c_{srtr}		Rotate along axis a which is vertical to rotating plane and then translate along the direction parallel to axis a.	scaling-ro-translation symmetry c_{ssrt}		the locations of symmetry elements arranged as rotation- translation symmetry, the sizes changed orderly
glide symmetry c_{sgl}		the direction of mirror and the direction of translation are vertical mutually	scaling-glide symmetry c_{ssgl}		the locations of symmetry elements are arranged as glide symmetry, the sizes change regularly
reversal symmetry c_{sre}		reversal symmetry can be regarded as combination of mirror symmetry and rotation symmetry	scaling-reversal symmetry c_{ssre}		the locations of symmetry elements are arranged as reversal symmetry, the sizes change regularly

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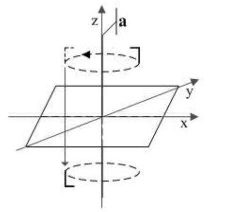
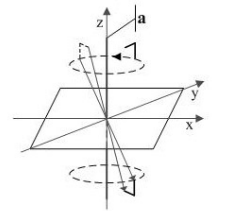
rotation-mirror symmetry c_{srmi}		Rotate along axis a and then carry out mirror operation by taking xy plane as datum plane	rotation-reversal symmetry c_{srre}		Rotate along axis a and then carry out reversal operation by taking xy plane as datum plane

Definition 3: If a mechanical system has one or more parts that have orderly time-changing process, then this mechanical system has process symmetry.

Process symmetry $c_{po}=<c_{pos}, c_{pom}>$, where: c_{pos} -single process symmetry, $c_{pos}=<c_{posp}, c_{poss}>$, c_{posp}-space movement process symmetry, the symmetry of space movement, c_{poss}-state process symmetry, the symmetry of transformation of materiel, energy or information; c_{pom} -multi-process symmetry, $c_{pom}=<c_{pomt}, c_{pomz}, c_{pomi}>$, there exists three relationship, namely translation, zoom and inversion, between multiple symmetry process.

For the crank-slider linkage in Figure 4, when crank AB moves at uniform speed, both the moving tracks of crank and slider are regular time-changing functions. The moving process of crank AB is a rotating symmetric circle track while the one of slider C is a reciprocating linear moving process. Therefore this mechanism has single moving process symmetry.

For the double-crank-slider in figure 5, the moving processes of crank AB and crank CD have identical time-changing law, so this mechanism has multi-process symmetry.

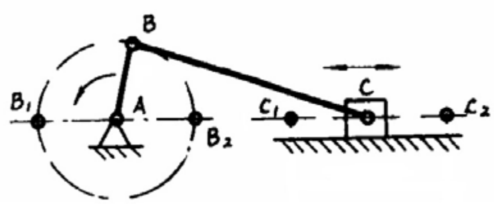


Figure 4: crank-slider linkage

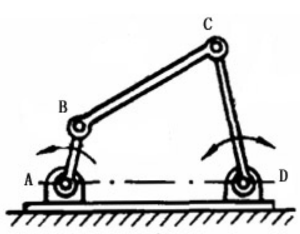


Figure 5: double-crank-slider

Definition 4: If a mechanical system has two or more functions and these functions can exchange, and the exchanges do not influence the realization of the function requirement of this system, then this mechanical system has function symmetry.

Function symmetry $c_f=<c_{fd}, c_{fe}>$, where c_{fd}-disassembly function symmetry, $c_{fd}=<c_{fdc}, c_{fds}, c_{fdcs}, c_{fdsc}, c_{fdr}>$, the disassembly types of function disassembly are showed in table 2; c_{fe} -exchange function symmetry, $c_{fe}=<c_{fes}, c_{fed}>$.

Figure 6 is the schematic diagram of the wheel fixing bolt. This mechanism has parallel disassembly function symmetry c_{fdc}. The five fixing bolts on wheel has the same function and co-work to implement the function of fixing wheel. If one of them doesn't work, the others can work normally, which is parallel function disassembly design.

Figure 7 is the schematic diagram of a single universal joint. This mechanism has exchange function symmetry. The driving shaft and driven shaft of the joint are two components with identical functions and they can exchange. However, each of them is indispensable, and they must mutually cooperate to implement the universal joint transmission.

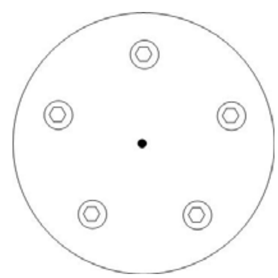


Figure 6: a wheel fixing bolt

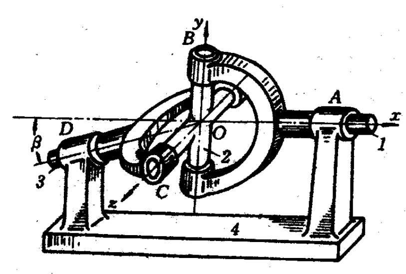


Figure 7: a single universal joint [17]

Definition 5: If a mechanical system has two or more principles and these principles can exchange, and these exchanges do not influence the realization of the principle requirement of the system, then this mechanical system has principle symmetry.

Principle symmetry $\mathbf{c_{pi}}$=< $\mathbf{c_{pid}}$, $\mathbf{c_{pie}}$>. where $\mathbf{c_{pid}}$ - disassembly principle symmetry, $\mathbf{c_{pid}}$=<$\mathbf{c_{pidc}}$, $\mathbf{c_{pids}}$, $\mathbf{c_{pidcs}}$, $\mathbf{c_{pidsc}}$, $\mathbf{c_{pidr}}$>, the disassembly types of principle disassembly are showed in table 2; $\mathbf{c_{pe}}$-exchange principle symmetry, $\mathbf{c_{pie}}$=<$\mathbf{c_{pies}}$, $\mathbf{c_{pied}}$>.

For the example in figure 8, to make the jamming plate 3 keep the direction of AB, this mechanism utilizes two symmetric springs to hold the two sides of jamming plate 3 and these two springs cooperate to realize the function requirement. The structure, function and principle of these two springs are all the same. Therefore, the two springs and jamming plate have mirror symmetry in structure, function symmetry in function and principle symmetry in principle.

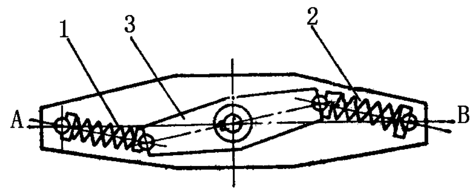
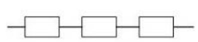
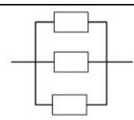
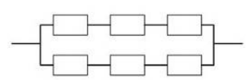
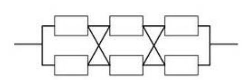


Figure 8: a structure having multi-level symmetry[19]

Table 2: sketch map of the style of decomposability

concurrent disassembly	seriation disassembly	seriation-concurrent disassembly	concurrent-seriation disassembly	reticulation disassembly
				

III. MS CONCEPTS' ATTRIBUTE SET CA_m

MS concepts' attribute set contains all the attributes of all the elements in MS concept set, $\mathbf{CA_m}$=<$\mathbf{ca_{mb}}$, $\mathbf{ca_b}$, $\mathbf{ca_o}$, $\mathbf{ca_{dn}}$, $\mathbf{ca_{ax}}$, $\mathbf{ca_{mt}}$, $\mathbf{ca_n}$, $\mathbf{ca_{df}}$, $\mathbf{ca_{dp}}$, $\mathbf{ca_{ds}}$, $\mathbf{ca_c}$, $\mathbf{ca_{th}}$, $\mathbf{ca_p}$, $\mathbf{ca_f}$>. In this set: $\mathbf{ca_{mb}}$ — main body of MS; $\mathbf{ca_b}$— level of MS, including four levels: function level, principle level, structure level and process level. $\mathbf{ca_o}$ — symmetric operation of MS, symmetric operation connected with symmetry closely, every symmetry corresponds to a symmetric operation; $\mathbf{ca_{dn}}$— dimensionality of symmetric structure; $\mathbf{ca_{ax}}$ —symmetric axis or symmetric plane of one symmetric structure; $\mathbf{ca_{mt}}$ — mathematical description of symmetry; $\mathbf{ca_n}$ — sum of elements of MS; $\mathbf{ca_{df}}$ —similarities and differences of elements' functions of MS. $\mathbf{ca_{dp}}$ — similarities and differences of elements' principle of MS. $\mathbf{ca_{ds}}$ —similarities and differences of elements' structure of MS. $\mathbf{ca_c}$ —combinability of MS, including common combinative symmetries and non-combinative symmetries; $\mathbf{ca_{th}}$ — theory of symmetry design; $\mathbf{ca_p}$ — principle of symmetry design; $\mathbf{ca_f}$ — function of mechanics symmetry, in a high level, the function can be divided into three types: economic function, technical function and social function.

MS concepts' attribute set $\mathbf{CA_m}$ has many elements, the attribute elements of each element of MS concept set $\mathbf{C_m}$ are a subset of $\mathbf{CA_m}$. Taking mirror symmetry $\mathbf{c_{smi}}$ as an example, the attribute $\mathbf{CA_{m(csmi)}}$ of $\mathbf{c_{smi}}$ is showed in table 3.

Table 3: the attribute $\mathbf{CA_{m(csmi)}}$ of $\mathbf{c_{smi}}$

	$\mathbf{ca_{mb}}$	$\mathbf{ca_b}$	$\mathbf{ca_o}$	$\mathbf{ca_{dn}}$	$\mathbf{ca_{ax}}$	$\mathbf{ca_{mt}}$	$\mathbf{ca_n}$	$\mathbf{ca_{ds}}$	$\mathbf{ca_c}$	$\mathbf{ca_{th}}$, $\mathbf{ca_p}$, $\mathbf{ca_f}$
$\mathbf{CA_{m(csmi)}}$	structure of mechanism	structure level	mirror operation	two-dimensional	symmetric axis is y axis	x_2=-x_1 y_2=y_1	2	same	it can be combined with $\mathbf{c_{str}}$, $\mathbf{c_{sro}}$, $\mathbf{c_{ssc}}$ and so on	
				three-dimensional	symmetric plane is y-z plane	x_2=-x_1 y_2=y_1 z_2=z_1				

IV. MS EXAMPLE SET E_m

MS example set $\mathbf{E_m}$ includes all mechanical systems and elements having symmetry. The elements of $\mathbf{E_m}$ could be some large and complicated mechanical systems, such as plane, auto, and engineering machine etc., and could also be some small and simple standardized parts and components, such as bolt, nut, and spring etc. Corresponding to MS concept set $\mathbf{C_m}$, $\mathbf{E_m}$ is also a hierarchical system. Figure 9 is a symmetric example- an oriented mechanism, marked as $\mathbf{E_{om}}$.

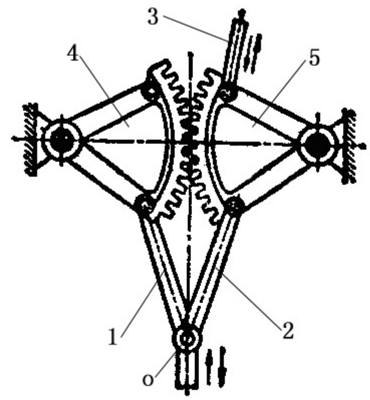


Figure 9: an oriented mechanism[18]

Table 4：the attributes matrix of $\mathbf{E_{om}}$

$\mathbf{ea_t}$	$\mathbf{ea_{mb}}$	$\mathbf{ea_b}$	$\mathbf{ea_o}$	$\mathbf{ea_n}$	$\mathbf{ea_{df}}$	$\mathbf{ea_{dp}}$	$\mathbf{ea_{ds}}$	$\mathbf{ea_c}$	$\mathbf{ea_{th}}$	$\mathbf{ea_p}$	$\mathbf{ea_f}$
1. disassembly function symmetry $\mathbf{c_{fd}}$	sector gear 4, link 1 and sector gear 5, link 2	function level	reticulation disassembly	2	same	—	—	—			
2. disassembly principle symmetry $\mathbf{c_{pid}}$	sector gear 4, link 1 and sector gear 5, link 2	principle level	reticulation disassembly	2	—	same	—	—			
3. rotation symmetry $\mathbf{c_{sro}}$	gear teeth	structure level	rotation operation	12	—	—	same	the four symmetries are hierarchical, No4 include No3, No6 is composed of No3, No4 and No5.			the rotation symmetric and mirror symmetric structures can ensure the up-down reciprocating linear motion of point “o”
4. mirror symmetry $\mathbf{c_{smi}}$	sector gear 4 and 5	structure level	mirror operation	—	—	—	—	—			
5. mirror symmetry $\mathbf{c_{smi}}$	link 1 and 2	structure level	mirror operation	2	—	—	—	—			
6. mirror symmetry $\mathbf{c_{smi}}$	sector gear 4, link 1 and sector gear 5, link 2	structure level	mirror operation	2	—	—	same	the four symmetries are hierarchical, No4 include No3, No6 is composed of No3, No4 and No5.			the rotation symmetric and mirror symmetric structures can ensure the up-down reciprocating linear motion of point “o”

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V. MS EXAMPLES' ATTRIBUTE SET EA_m

MS examples' attribute set $\mathbf{EA_m}$ is the description of MS example set $\mathbf{E_m}$. $\mathbf{EA_m}$ can be described by a two-dimensional matrix: the row element is the symmetry type of MS example $\mathbf{ea_t}$; the column elements include {$\mathbf{ea_{mb}}$, $\mathbf{ea_b}$, $\mathbf{ea_o}$, $\mathbf{ea_n}$, $\mathbf{ea_{df}}$, $\mathbf{ea_{dp}}$, $\mathbf{ea_{ds}}$, $\mathbf{ea_c}$, $\mathbf{ea_{th}}$, $\mathbf{ea_p}$, $\mathbf{ea_f}$}, where: $\mathbf{ea_{mb}}$ — main body of symmetry, $\mathbf{ea_b}$ — symmetry level, including four levels: function level, principle level, structure level and process level, $\mathbf{ea_o}$ — symmetric operation, different for different main body, $\mathbf{ea_n}$ — sum of symmetric elements, $\mathbf{ea_{df}}$ —similarities and differences of elements' functions of symmetry examples, $\mathbf{ea_{dp}}$ — similarities and differences of elements' principle of symmetry examples, $\mathbf{ea_{ds}}$ — similarities and differences of elements' structure of symmetry examples, $\mathbf{ea_c}$ — combinability of example's symmetry, an complicated example can have many kinds of symmetry and these symmetries may be combined with some hierarchical rules, $\mathbf{ea_{th}}$ — theory of symmetry design, $\mathbf{ea_p}$ — principle of symmetry design, $\mathbf{ea_f}$ — function of mechanics symmetry, the same to $\mathbf{ca_f}$, $\mathbf{ea_f}$ and can also be divided into three types of functions: economic function, technical function and social function. Taking $\mathbf{E_{om}}$ as an example, the attribute matrix of $\mathbf{EA_{m(Eom)}}$ is showed in table 4.

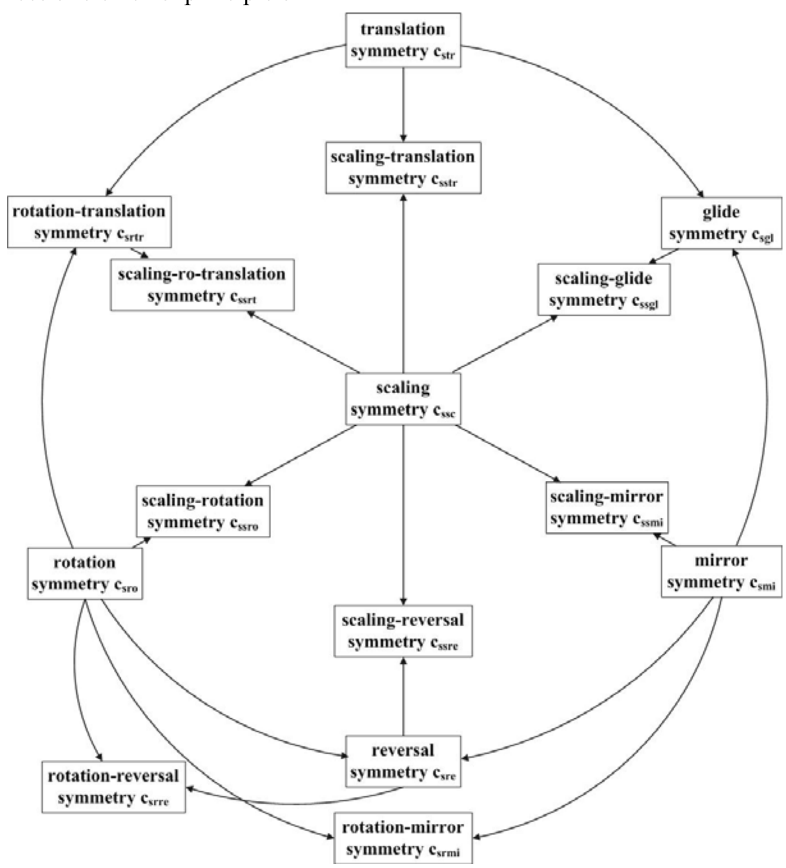

Figure 10: the combinational relationship between structure symmetry

VI. MS RELATIONSHIP SET R_m

MS relationship set $\mathbf{R_m}$ describes the interior relationships and interrelation between the elements of MS ontology, such as $\mathbf{C_m}$, $\mathbf{CA_m}$, $\mathbf{E_m}$, $\mathbf{EA_m}$.

——In MS concept set $\mathbf{C_m}$, there are two kinds of affiliating relationship in the elements in the same class: "equal to" and "is a". If concept c_1 and c_2 are completely the same, then c_1 equal to c_2, marked as $c_1 \equiv c_2$. If concept c_1 is a subclass of c_2, then c_1 is a c_2, marked as $c_1 \subseteq c_2$, such as $\mathbf{c_{pies}} \subseteq \mathbf{c_{pie}}$, $\mathbf{c_{str}} \subseteq \mathbf{c_s}$, $\mathbf{c_{sre}} \subseteq \mathbf{c_s}$.

——The combinational relationship between structure symmetry $\mathbf{c_s}$ in MS concept set $\mathbf{C_m}$. The elements in combinational structure symmetry $\mathbf{c_{sc}}$ are composed of the elements in basic structure symmetry $\mathbf{c_{sb}}$. For instance, rotation-translation symmetry $\mathbf{c_{srtr}}$ is composed ofrotation symmetry $\mathbf{c_{sro}}$ and translation symmetry $\mathbf{c_{str}}$ and reversal symmetry $\mathbf{c_{sre}}$ is composed by mirror symmetry $\mathbf{c_{smi}}$ and rotation symmetry $\mathbf{c_{sro}}$. The specific combinational relationship is showed in figure 10.

——In MS concept set $\mathbf{C_m}$, there is a relationship called "mapped" between the elements in different levels. The elements in function symmetry $\mathbf{c_f}$, principle symmetry $\mathbf{c_{pi}}$, structure symmetry $\mathbf{c_s}$ and process symmetry $\mathbf{c_{po}}$ have a multi to multi bidirectional mapped relationship, showed in figure 11.

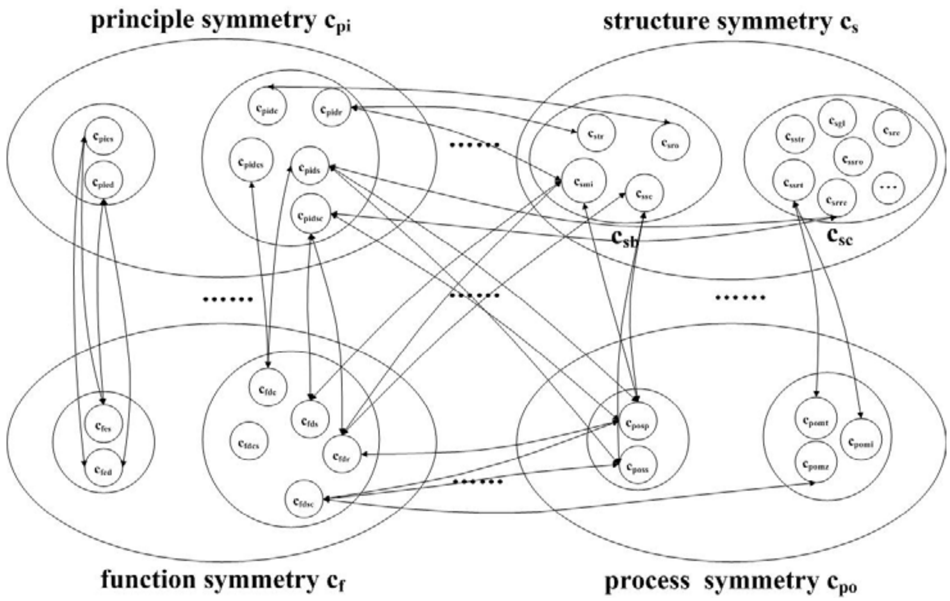

Figure 11: the mapped relationship between the levels in $\mathbf{C_m}$

——The elements in MS concepts' attribute set $\mathbf{CA_m}$ are detailed descriptions of the elements in MS concept set $\mathbf{C_m}$, and the relationship between $\mathbf{C_m}$ and $\mathbf{CA_m}$ is a multi to multi unidirectional mapped relationship, showed in figure 12. Similarly, the elements in MS examples' attribute set $\mathbf{EA_m}$ are detailed descriptions of the elements in MS example set $\mathbf{E_m}$, and the relationship between $\mathbf{E_m}$ and $\mathbf{EA_m}$ is still a multi to multi unidirectional mapped relationship, showed in figure 13.

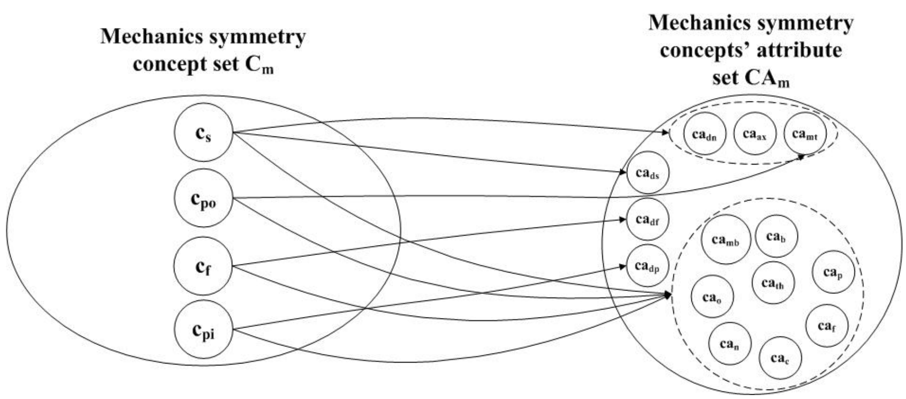

Figure 12: the relationship between $\mathbf{C_m}$ and $\mathbf{CA_m}$

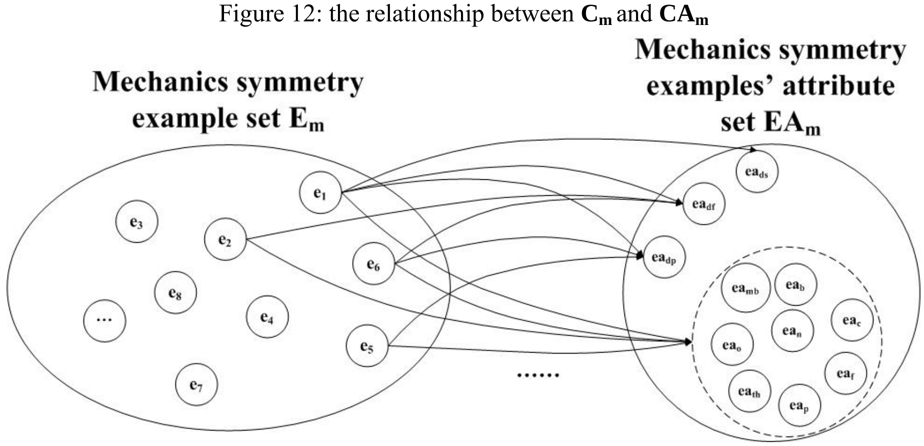

Figure 13: the relationship between $\mathbf{E_m}$ and $\mathbf{EA_m}$

——The elements in MS example set $\mathbf{E_m}$ are the instantiation of the elements in MS concept set $\mathbf{C_m}$, the relationship between $\mathbf{C_m}$ and $\mathbf{E_m}$ is a multi to multi unidirectional mapped relationship, showed in figure 14. Similarly, $\mathbf{CA_m}$ and $\mathbf{EA_m}$ is also a multi to multi unidirectional mapped relationship, showed in figure 15.

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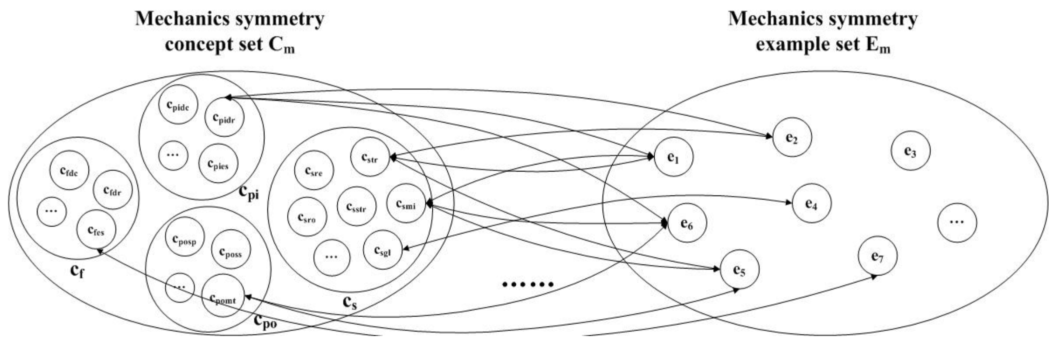

Figure 14: the relationship between $\mathbf{C_m}$ and $\mathbf{E_m}$

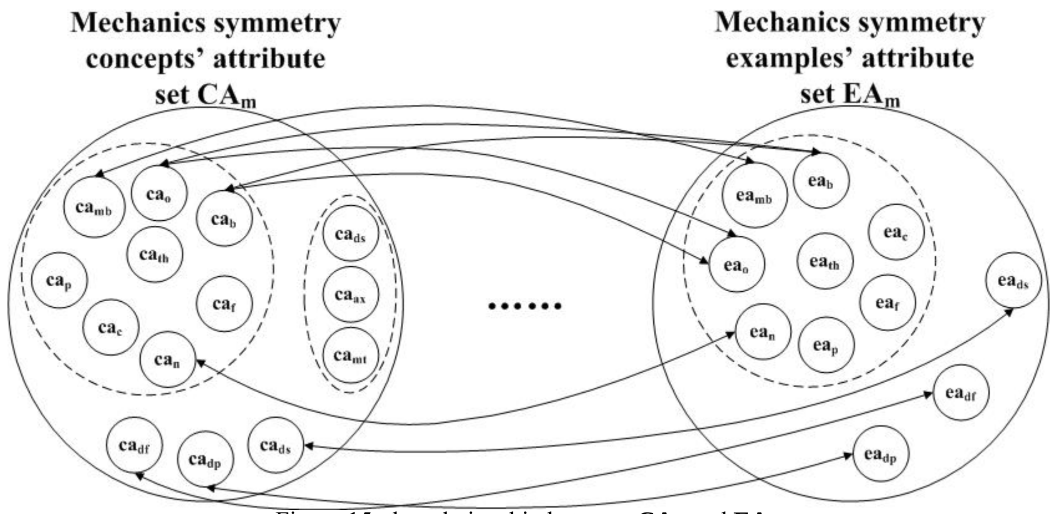

Figure 15: the relationship between $\mathbf{CA_m}$ and $\mathbf{EA_m}$

VII. CONCLUSION

Symmetry exists anywhere in mechanical system and mechanical engineering, in which it plays an important role. The research on concept, principle, rule of MS is helpful to further understand the objective laws of product design and mechanical systems, benefit innovative design, enhance the efficiency of product design, and improve technology, economy, sociality of product design. In this paper, a framework of mechanics symmetry ontology was established; the definitions and descriptions of the concepts in MS and the relationships and descriptions of the elements in MS ontology in the definition range were proposed. Moreover, this paper established foundation for further research on MS examples and the principles of MS. Further achievement will be posted latterly

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