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Structural classification of planetary gear-cam mechanisms

Farah Saoud*, Sajad Abdali, Essam Esmail

Department of Mechanical Engineering, College of Engineering, University of Al-Qadisiyah, Al-Qadisiyah, Iraq

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ABSTRACT

Planetary gear-cam mechanisms (PGCMs) are mechanisms that combine planetary gears and cams. Despite the fact that these systems have the ability to achieve a wide variety of periodic motions of the output link, they have received little attention. To generate and classify PGCMs, structural properties must first be identified. The classification of gear-cam mechanisms is studied, as well as their functional, structural, and graph representations. PGCMs are classified based on their number of degrees of freedom, number of links, and joint kinds. They are synthesized utilizing the spanning tree-based approach to build the entire set of gear-cam graphs. The relation between graphs and PGCMs is investigated and many graph fundamentals are converted into PGCMs. The atlas of five-vertex graphs is obtained, allowing the development of a large number of mechanisms. The precise results of the 5-link PGCM graphs have been confirmed to be 12. The application and significance of this approach in producing a variety of non-uniform motions, developing better alternatives, and creating new designs for variable-speed output mechanisms are demonstrated.

1. Introduction

To facilitate the cyclic motion of the output link of input mechanisms in numerous industrial machines, such as those employing packaging, printing, textile, and paper machinery, it is necessary to accomplish a controlled speed over the course of an operation cycle. Processing industries must improve their productivity and efficiency. As a result, high-productivity and high-reliability machines are in high demand. As a result, design trends favour high-speed machines with high accuracy, low noise, and low energy consumption. For example, Figure 1 depicts the rotating table of an indexing machine [1]. The process is carried out in a series of operations that take place at various stations. At each station, the relative velocity between the tools and workpieces must be zero. As a result, the table will perform an indexed movement. The indexing machine transforms the constant speed of the input motor into the intermittent motion of the worktable.

To achieve high-speed movements, irregular drive mechanisms such as the Geneva mechanism, star wheel, or ratchet mechanism are avoided due to the jerk that occurs when these mechanisms are used in high-speed machinery that has massive moving masses. This situation has a lot of power and load, and the best way to meet it is often to combine cams and gears that are all driven by a motor or engine at a steady speed. Accuracy, dependability, minimal vibration, and low noise may be obtained even when large masses are moved at rapid speeds. Cams provide all of the benefits of controlled design by enabling diversity in choosing the type of follower action, resulting in the optimum dynamic features of the mechanism.

* *Corresponding author.*
E-mail address: author@institute.xxx (Author name)

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Nomenclature:

PP	The prismatic- prismatic	*Subscripts*	
RR	The Revolute-Revolute	PGCM	PGCM
PR	The Prismatic –Revolute	PGT	PGT
F	The number of degrees of freedom	DOF	DOF
D	The vertex degree array\ =[d_0,\ d_1,\ \ldots,\ d_{v-1}]	IVT	IVT
v	Number of vertices in the graph	LAA	LAA

If a mechanism has gear pairs, it is termed a geared mechanism; if it contains cam pairs, it is called a cam mechanism; and if it contains both gear and cam pairs, it is called a gear-cam mechanism [2]. Three lower pairs and two upper pairs are typically employed in gear-cam mechanisms. Revolute (R), prismatic (P), and cylindrical (C) pairs are lower pairs, while higher pairs are cam and gear pairs. In the worm and worm gear system shown in Fig. 2, shaft A propels worm gear C through worm B. An immobile roller in the rotating cam E causes the reciprocating and rotating motion of shaft A. As a result, the output of the worm gear consists of the rotation of the input shaft in addition to its axial movement. Figure 3 depicts a compound PGT with gear A as the driving gear.
The output of the planet gear as well as the movement of the carrier drive Gear D.Figure 4 depicts a kinematically identical design to the previous one. As stated previously, the output speed is the sum of two motions: the inputs of both gear A and planet gear carrier G, where G is driven by the cam. Gear A drives gear B, which turns the planetary gear C, which meshes with gear D on the output shaft. Gear C can freely rotate on its shaft. Gear E is driven by rack F, which is attached to the cam follower. As a result, the output is comprised of the cam and gear A inputs. Figure 5 shows a PGCM with a fixed cam. The planet carrier as well as the planet gear are both driven by the sun gear. The output of the carrier is propelled by the rotation of the planet gear in conjunction with the rotation of the follower in its fixed cam groove. Figure 6 depicts an indexing mechanism made up of a planetary gear and a cam. A planet gear and a cam are fixed in relation to one another, while the carrier rotates at a constant speed around the fixed sun gear. The index arm moves non-uniformly and has dwell periods.
There are two types of PGCMs: those with a fixed link and those with all links moving. Despite the great number of PGCM structural variations, there are very few mechanisms that are actually useful. Mechanisms with few links are preferred in practical designs for their simplicity. Therefore, PGCMs with six or more links have little use in the real world. PGCMs with a fixed link are simple, have few links, and are widely used.

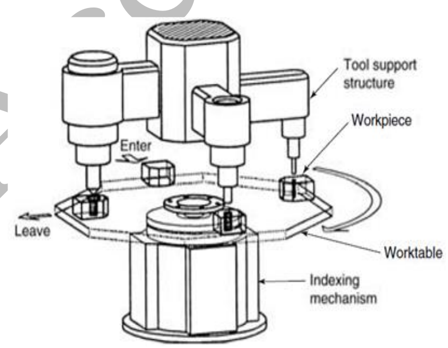


Figure 1. Indexed movement of the worktable [1]

PGCMs appear to be a suitable alternative for the creation of indexed motion. Their applications are not limited to indexing mechanisms; they can be used for exact path generation mechanisms [4], rigid body guidance mechanisms [5], and infinitely variable transmissions [6].

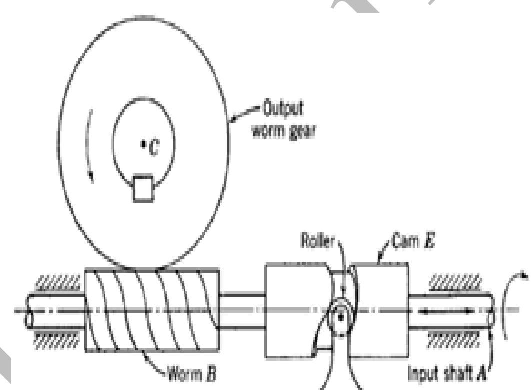


Figure 2. Gear-Cam mechanism with worm gear drive [1]

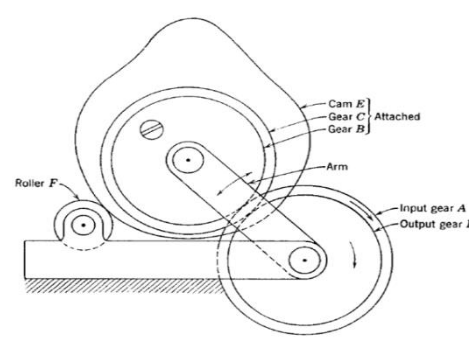


Figure 3. PGCM with fixed follower [1]

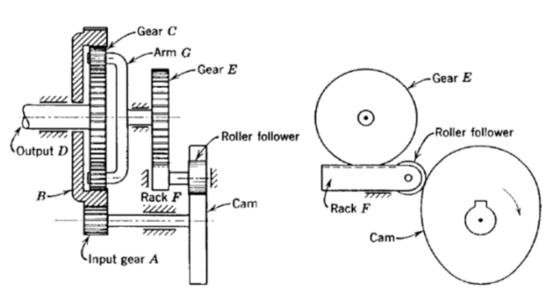


Figure 4. Planetary Gear-Cam mechanism [1]

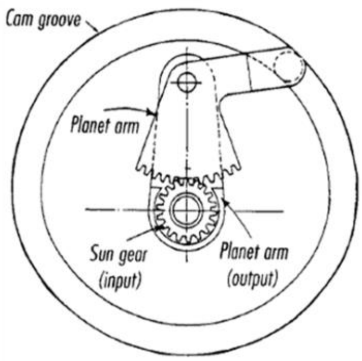


Figure 5. Planetary Gear-Cam mechanism with fixed cam [3]

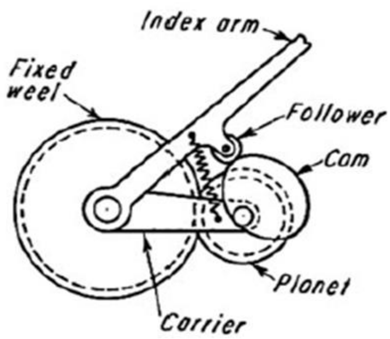
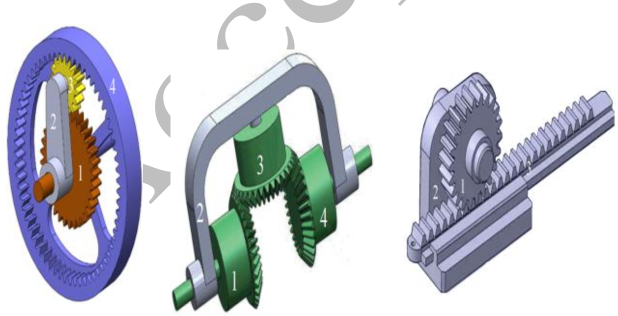


Figure 6. Planetary Gear-Cam mechanism with fixed sun gear

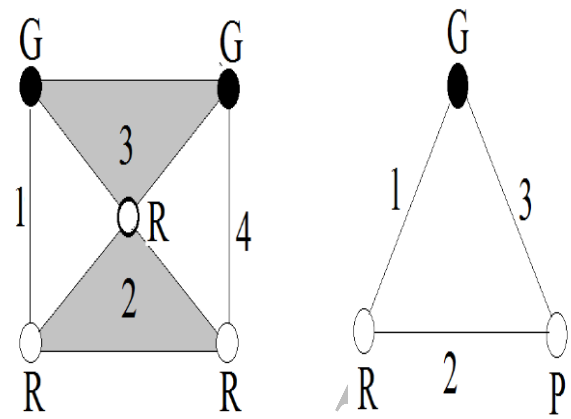
1.1 Planar geared mechanisms

A planar geared mechanism is a geared kinematic chain that contains only prismatic, P, revolute, R, and gear joints, G. A planetary gear train (PGT) is a gear train that includes a supporting link between each pair of meshing gears to maintain the distance between them constant. This supporting link is known as a carrier. The most basic types of gear trains with supporting links are shown in Figure 7.



(a) (b) (c)

Figure 7. Basic types of gear trains with a supporting link.
(a) Spur gear , (b) Bevel gear , (c) Rack and pinion



(a) (b)

Figure 8. Structural representation of the PGTs shown in Fig. 7.
(a) Spur or Bevel gears ,(b) Rack and pinion

A polygon with vertices that represent the kinematic pairings serves as the structural representation of each link in a mechanism. Figure 8 illustrates the structural representation of the PGTs illustrated in Figure 7. We observe that the type of gear mesh cannot be determined at that level of abstraction. In this respect, the functional representation shown in Fig. 8 (a) represents the sketch of more than one kinematic structure (Fig. 7 (a) and (b)). Either gear pair can assume either spur or bevel gears, external or internal gear mesh, or rack and pinion. Consequently, there is NO exact correspondence between both structural and functional representations. To identify the differences, an additional level of clarity is required. Kinematic inversion allows for the derivation of a wide variety of gear mechanisms. If, for instance, the carrier of a PGT is designated as the stationary link, the resulting mechanism is a conventional gear train. Ordinary gear trains can be considered special cases of PGTs.

1.2 Planetary gear trains

A PGT is a geared kinematic chain that contains only revolute and geared joints and conforms to the rules below [2]:

- R1. The mechanism must follow the general equation of degrees of freedom.
- R2. All links must be rotatable unlimitedly.
- R3. Each gear needs to have a revolute joint on its axis so as to keep a constant centre spacing between gear pairs.
- R4. Every link must include at least one revolute joint in order to function properly.

PGTs are not only small and lightweight, but they are also capable of creating a large mechanical advantage as well as a high-speed single-stage reduction. PGTs are frequently used in robotic manipulators [7], automatic transmissions [8–11], and aerospace drives such as helicopter transmissions [12–15] or wind turbine reduction gears [16]. The transmission depicted in Figure 9 is infinitely variable and capable of achieving any transmission ratio. This transmission has five primary components in its most basic form. A three-dimensional cam is in the centre. A few followers are mounted on the carrier around the camp. The rotation of the carrier causes the followers to revolve about the axis of the cam. An indexing clutch, shown in Figure 10, connects the output shaft to all of the sun gears.

1.3 Cam mechanisms

The simplest cam mechanism consists of three components: the cam, the cam-follower, and the housing. Prismatic, revolute, cylindrical, or screw pairs can be used to connect the frame to the cam or follower [1]. Three features distinguish cams from other mechanisms:

1. Greater velocity capability
2. Capability to impart larger torque at higher momentum, and
3. Reliable performance that is characterized by great repeatability and accuracy [2].

The follower in Figure 4 has a translator motion, whereas the followers in Figures (5), (6), and (9) all have a rotary motion. We also use the notation (P) for prismatic joint, (R) for revolute joint, and (C_p) for cam pair when referring to cam mechanisms. Hence, we have RRC_p,\ RPC_p,\ and\ PPC_p

There are three different kinds of joints used in cam systems, as shown in Figure 11. Computer-aided design (CAD) can be used to generate highly accurate cam profiles. Furthermore, the use of computer-aided manufacturing (CAM) has significantly improved the accuracy of cam machining. Cam mechanisms are used for a variety of purposes, including speed reduction.

1.4 Exact path generation

Path generation is the process of producing a trajectory for a given point along a predetermined path [17]. Soong [18] created a PGCM for accurate path generation by combining a cam-follower with a PGT. The different links of the PGCM are differentiated by number and colour in Fig. 12. If the ratio between the planet and sun gears is one, the coupler point p can create a specified path while the input link makes a single cycle.

1.5 Rigid body guidance

Motion generation can be defined as the control of a planar link to move through a specified set of successive locations. Soong [19] proposed a rigid body guidance PGCM consisting of two cams with two followers, translating and oscillating. A rigid-body guided PGCM operated by a rotating input link is shown in Figure 13.

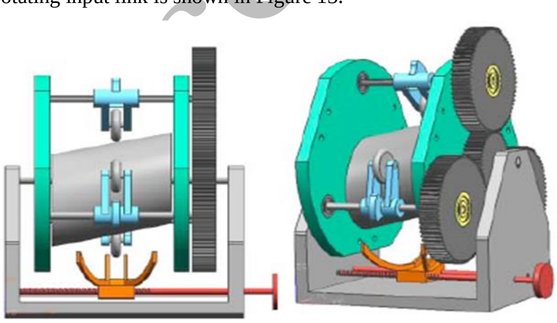


Figure 9. The front and isometric view of the cam-based infinitely variable transmission [13]

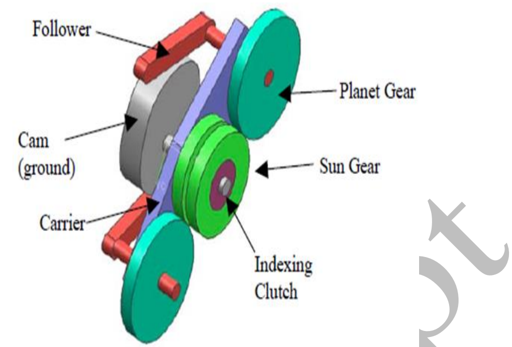
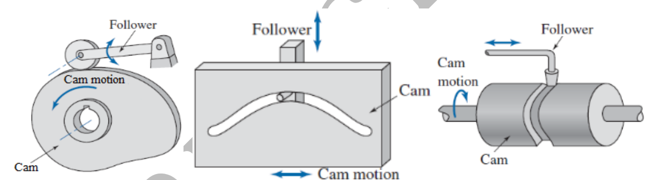


Figure 10. Simplified depiction of the IVT [13]



(a) (b) (c)

Figure 11. Three types of cam mechanisms joints. (a) RR Cam pair , (b) PP Cam pair , (c) RP Cam pair

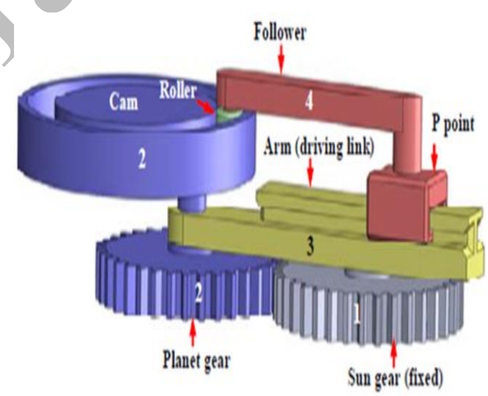


Figure 12. Exact path generation mechanism [18]

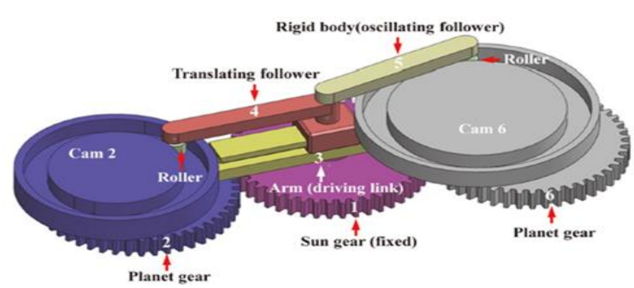
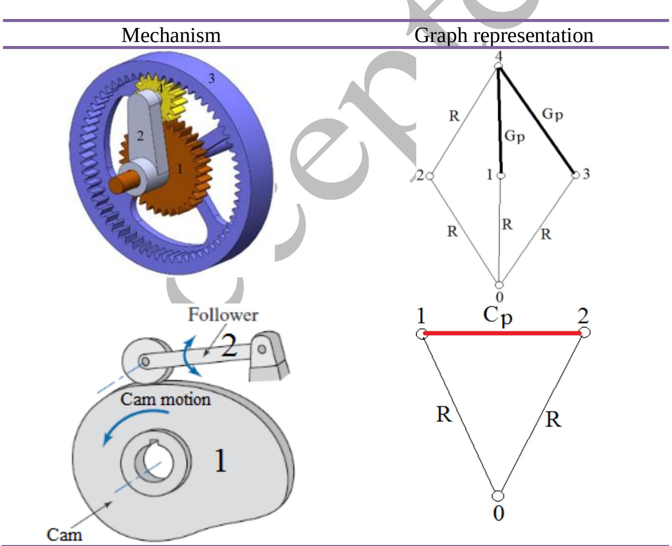


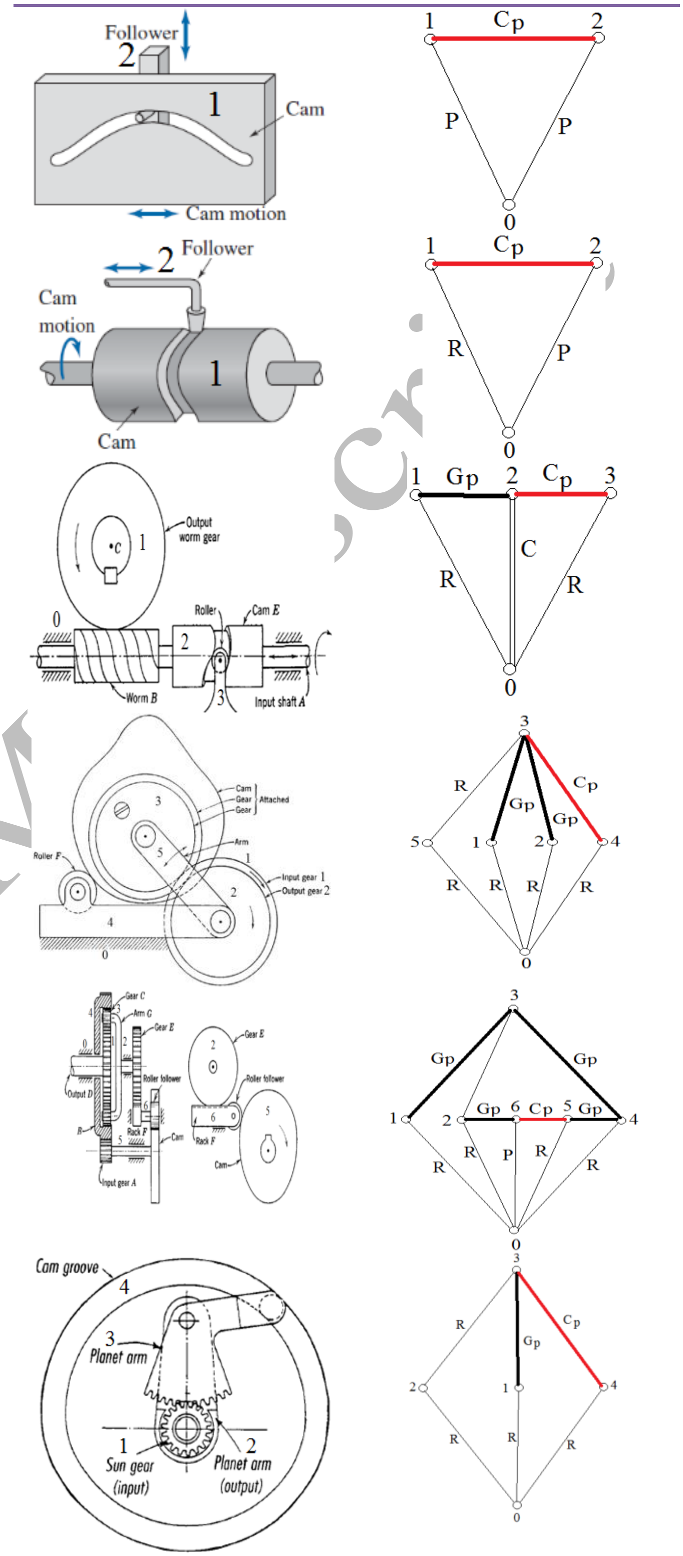
Figure 13. A rigid body guidance planetary gear-cam mechanism [19]

2. Graph representation

The graph representation of a mechanism is created by representing each link as a vertex and each joint as an edge [20]. Each edge connection between two vertices corresponds to a link-to-link joint connection. The graph completely ignores the dimensions of the mechanism, preserving only information about the number of links and the type of joints connecting them. A graph is said to be rooted if one of its vertices stands out from the others [21]. In the mechanism, the root represents a unique link, which is usually the ground link (or the frame). Because it is easier to enumerate rooted graphs, one should always attempt to employ the ground link when generating a class of mechanisms. For convenience, we utilize a thick edge to indicate a gear joint, a thin edge to indicate a revolute or prismatic joint, and a thick red edge to indicate a cam joint. Figure 14 is a graphical representation of PGTs, cams, and followers, as well as PGCMs. GCMs should be able to produce non-uniform motion in order to be a better candidate for driving variable-speed input mechanisms. Gear cam mechanisms can be classified into two groups, each with its own set of structural characteristics depending on their gear train structures. The first group contains ordinary gear trains, while the second group contains only planetary gear trains [22-27]. The structural synthesis of PGCMs has only been the focus of little research in the past [24]. Because planetary gear-cam mechanisms are of particular relevance to this work, the section that follows will concentrate on their structural characteristics. Furthermore, four- and seven-link gear-cam mechanisms like those shown in Figures 2 and 4 that have in their structures conventional gear trains should be excluded from further consideration.

Based on R2 and R3 above, the gear-cam mechanism with worm gear drive discussed before is an ordinary gear-cam mechanism. When the planet gear in a PGCM is fixed, the planetary gear-cam mechanism transforms into a conventional gear-cam mechanism.





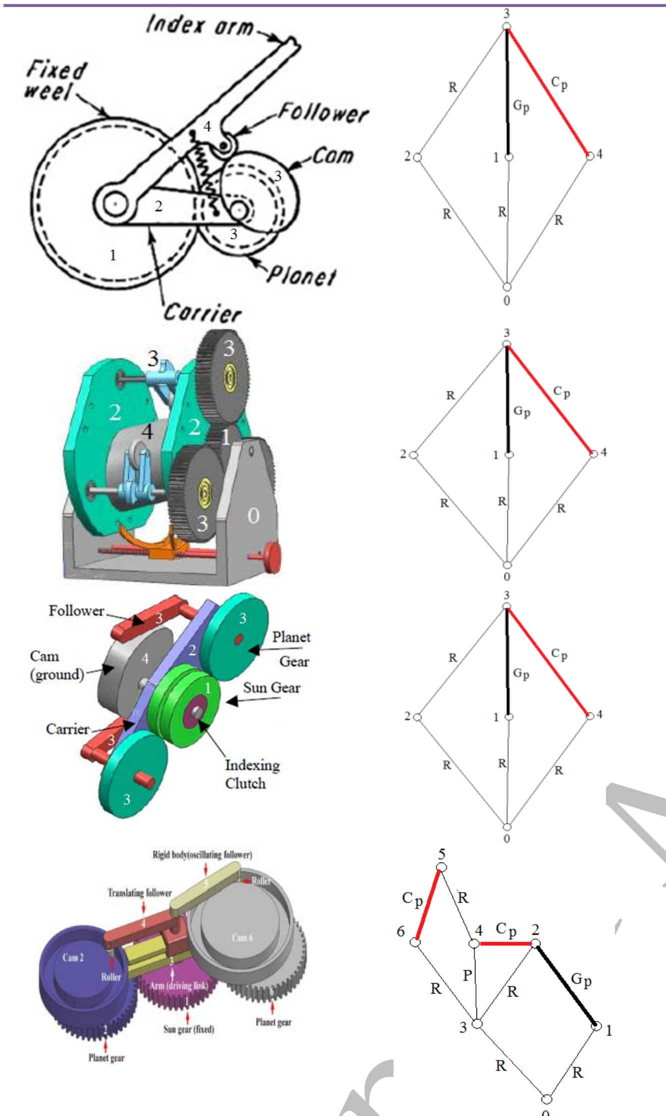
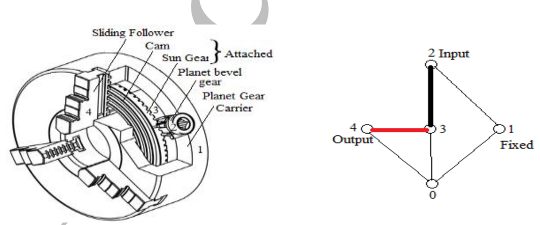


Figure 14. Rooted graphs for different GCMs.



(a) (b)

Figure 15 .Three-jaw self-centering chuck. (a) The three-jaw self-centring chuck (b)Its graph representation

For example, the three-jaw self-centering chuck, shown in Fig. 15 (a), is a type of PGCM with the planet carrier relatively fixed. Figure 15 (b) illustrates the graph representation of the three-jaw chuck and the input and output links. For the links of the PGT part of the PGCM to possess unlimited rotation (Rule 2), the joints will all be revolute. Consequently, only gear and revolute joints are permitted for the structure synthesis of the PGT part of the mechanism. For the cam-follower mechanism, the prismatic joint is included.

3. Classifying two-DOF planetary gear-cam mechanisms

Let the number of i-DOFs be represented by j_i, therefore,

$$j = j_1 + j_2 \quad (1)$$

Since the prismatic and revolute joints have one degree of freedom and the cam and geared joints have two degrees of freedom, the total DOF in all joints may be stated as

$$\sum_{i=1}^{j} f_i = j_1 + 2j_2 \quad (2)$$

The DOF of a mechanism can be written according to the Grübler or Kutzbach criteria for n-link, j-joint PGCM as follows:

$$F = \lambda(n - j - 1) + \sum_{i=1}^{j} f_i \quad (3)$$

where λ is the motion parameter and is equal to 3 for planar and spherical mechanisms. Substituting Eq. (1) and λ=3 into Eq. (3) yields:

$$F = 3(n-1) - 2j_1 - j_2 \quad (4)$$

According to R4, the number of lower pair joints is always one less than the number of links.

$$j_l = j_1 = n - 1 \quad (5)$$

According

Substituting Eq. (4) into Equation (3) yields

$$j_2 = n - 1 - F \quad (6)$$

For two-DOF PGCMs,

$$j_2 = n - 3 \quad (7)$$

As previously explained, a PGCM combines gear and cam components. Due to the fact that both components have joints with two degrees of freedom, each PGCM will have a minimum of two joints with two degrees of freedom. The number of two-DOF joints is :

$$J_2 \geq 2 \quad (8)$$

By substituting Eq. (7) into Eq. (6) and simplifying, we get:

$$n \geqslant 5 \quad (9)$$

Hence, any two-DOF PGCM must have at least five links. For $n = 5$ and $F = 2$, Eqs. (4) and (6) result in $J_1 = 4$ and $J_2 = 2$. In light of this, planar two-DOF PGCMs with five links have four one-DOF joints, one cam joint, and one geared joint. As previously discussed, the joints of the PGT part of the PGCM are all revolute joints, thus, the three one-DOF joints associated with the geared joint are revolute joints. The fourth one-DOF joint might be revolute or prismatic. The classification of two-DOF PGCMs with up to seven links is shown in Table 1 according to n , F, J_1, and J_2.

Table 1. Classification of two-DOF PGCMs with up to 7 links

Class	No. of Links n	No. of Degrees of freedom F	No. of 2-dof Joints j_2 (Eq. 6)		No. of 1-dof Joints j_1 (Eq. 4)	
1	5	2	2		4	
			Gear	cam	R	P
			1	1	4	0
					3	1
2	6		3		5	
			Gear	cam	R	P
			2	1	5	0
					4	1
			1	2	5	0
					4	1
					3	2
3	7		4		6	
			Gear	cam	R	P
			3	1	6	0
					5	1
			2	2	6	0
					5	1
					4	2
			1	3	6	0
					5	1
					4	2
					3	3

3.1. Identifying the structural characteristics of PGCMs

The structural characteristics for PGCMs are shown in Table 2.

Table 2. The structural characteristics for PGCMs

property	Structural characteristics
Mechanism type	planar planetary gear-cam mechanism
Degree of freedom	planar PGCMs are two-DOF geared mechanisms
Link types	gear, carrier, cam, follower and ground link (0).
Joint types	revolute (R), and prismatic (P)
Ground link	binary or ternary link
No redundant connections or partially rigid sub-chains shall be permitted.	

4. Structure synthesis of planetary gear-cam mechanisms

To construct the whole set of gear-cam graphs, PGCMs are synthesized using the spanning tree-based method. Figure 16 illustrates the major steps of the synthesis process.

Assume that the number of vertices of degree i is denoted by v_i , then

$$\sum_i^k v_i = v = n \qquad (10)$$

Using the fact that k (the maximal degree of a vertex) is greater than the j_2 by one, we have

$$k = j_2 + 1 \qquad (11)$$

Because each edge has two end vertices with which it is incident, it adds two to the total sum of the degrees of the vertices.

$$\sum_i^k i v_i = 2j \qquad (12)$$

The lower bond is $i = 1$ for spanning trees and $i = 2$ for parent graphs.

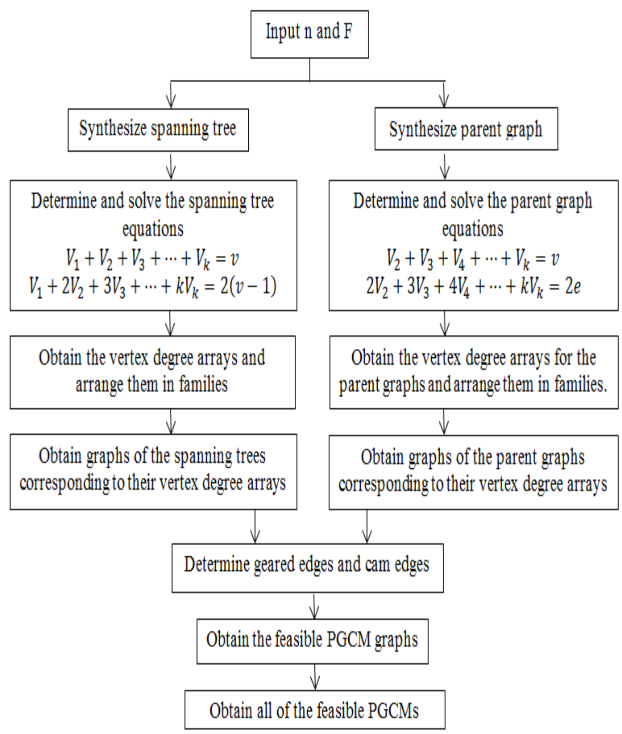
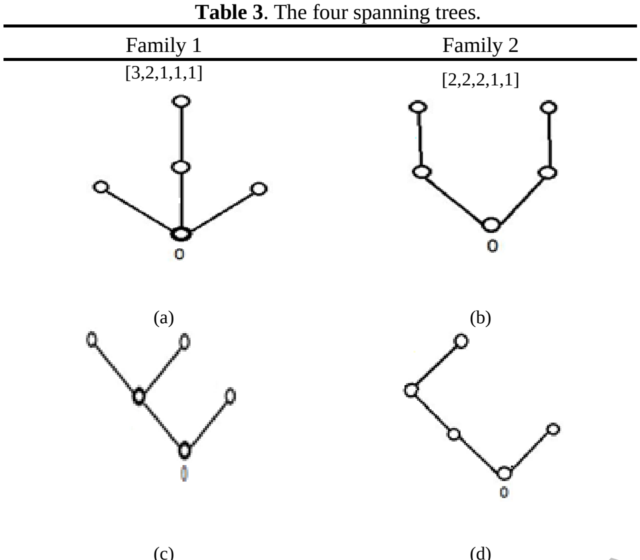


Figure 16. Flow chart for the structure synthesis of PGCMs.

4.1. Spanning Trees

The link assortment Array (LAA) for a spanning tree is designated as $[v_1, v_2, v_3, v_4, \ldots, v_k]$. The LAA satisfies Eqs. (9) and (11). All feasible LAAs can be derived for a given n and F. For instance, two LAAs can be obtained for 2-DOF 5-link PGTs: [2, 3, 0] and [3, 1, 1]. The vertex degree array (VDA) $[d1, d2, d3 \ \ldots \ldots \ dN]$ is obtained by ordering the degrees of vertices in a descending manner. For instance, the LAA [2,3,0] means that there are two pendant vertices and three binary vertices, so the corresponding degree array is [2, 2, 2, 1, 1]. By considering all the LAAs in turn, all possible candidate spanning trees can be synthesized. The four spanning trees that correspond to the two VDAs [2, 2, 2, 1, 1] and [3, 2, 1, 1, 1] are shown in Table 3.

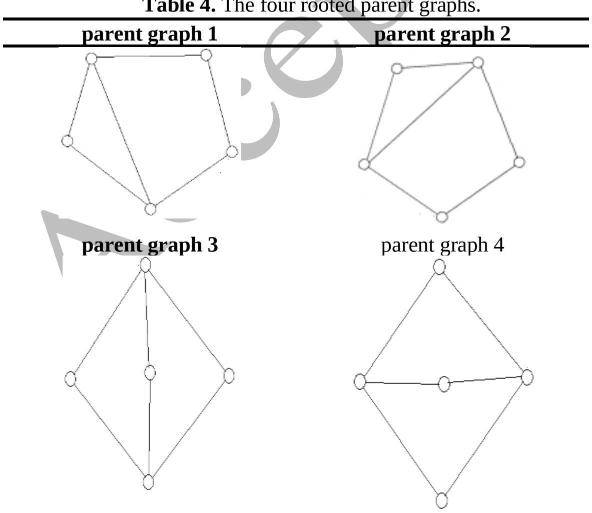
Table 3. The four spanning trees.



4.2. Parent graphs

The link assortment array (LAA) for a parent graph is designated as $[v_2, v_3, v_4, \ldots, v_k]$. For $F = 2$ and $v = 5$, only one LAA can be derived from Eqs. (9) and (11), namely, [3 2] and the corresponding vertex-degree array is [3, 3, 2, 2, 2]. Table 4 shows the four parent graphs for this vertex degree array.

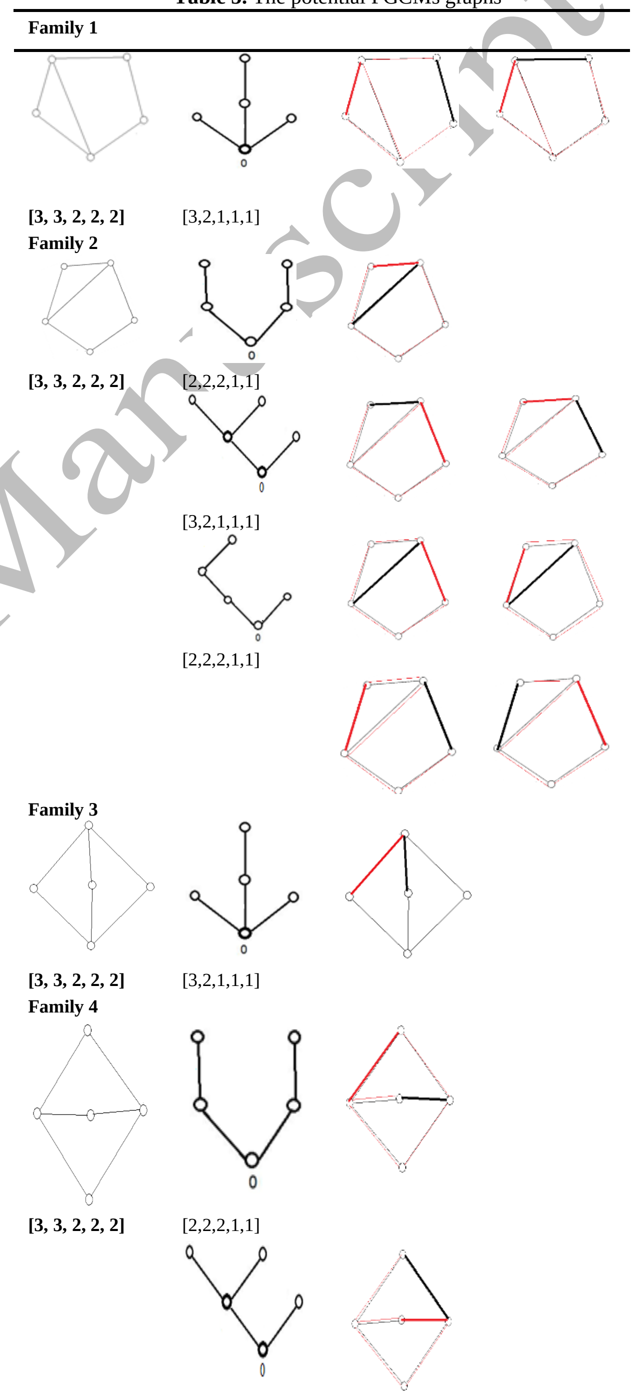
Table 4. The four rooted parent graphs.



4.3. Enumeration of geared-cam graphs

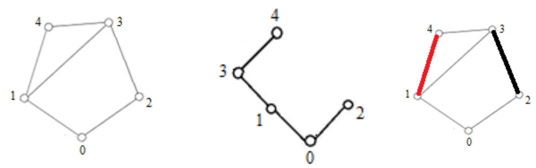
Table 5 shows how to identify geared and cam edges by comparing spanning trees from different families with parent graphs [29]. This process is known as "genetic compatibility" [30]. Table 5 shows potential PGCM graphs.

Table 5. The potential PGCMs graphs



	[3,2,1,1,1]

For the graphs in Figure 17, vertex 1 is the carrier of the planet gear 3, vertex 2, is a coaxial gear, and vertex 4 is the follower of cam 1.



(a) (b) (c)

Figure 17. The cam and geared edges are detected using the variation between the spanning tree and the parent graph. (a) Rooted parent graph, (b) spanning tree, and (c) PGCM graph.

Figure 18 shows a functional diagram that corresponds to Fig. 17 (c).

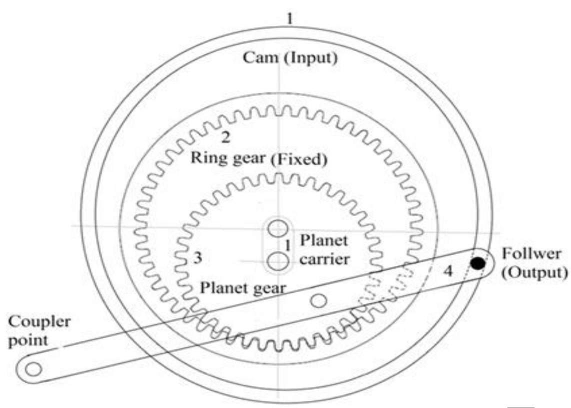


Figure 18. Functional diagrams that correspond to Figure 17 (c).

This new path-generation mechanism is a 5-link PGCM with 3R, G_p, and C_p. The PGT consists of ring gear 2, planet gear 3, and planet carrier 1. Planet carrier 1 is coupled to the cam and acts as an input link, while ring gear 2 is fixed. The path of the coupler point is determined by the motion of the roller in the moving-cam groove and the motion of the follower around the axis of the planet gear. The new mechanism is simple and compact, and it can generate continuous and symmetric curve paths.

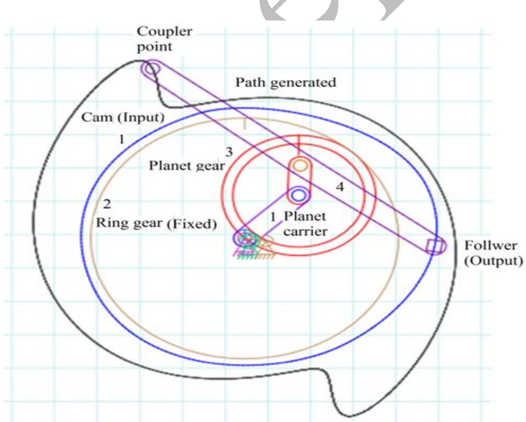


Figure 19. The path generated from the simulated mechanism.

5. Results and discussion

This work presents a systematic process for creating and categorizing PGCMs. The Classification of two-DOF PGCMs with up to 7 links is shown in Table 1. Studying the structural characteristics of the planetary gear cam mechanism is the basis for developing methods for systematic mechanism enumeration. The structural characteristics of PGCMs are shown in Table 2. The mechanical structures and working principles of different kinds of planetary gear cam mechanisms are summarized. Published papers on PGCMs are reviewed. Despite the great number of PGCM structural variations, there are very few mechanisms that are actually in use. Graphs are used for the systematic classification of PGCMs. Planetary geared-cam mechanisms are categorized based on the number of links (n), the number of degrees of freedom, and the number of one- and two-DOF joints. Mechanisms with few links are preferred in practical designs for their simplicity. PGCMs are categorized into two types based on their gear train topologies: those with conventional gear trains and those with only PGTs. The relation between graphs and PGCMs is investigated, and many graph fundamentals are converted into PGCMs. Rooted graphs for different GCMs are shown in Fig. 14. PGCMs were categorized based on their DOF, n, and joint kinds. The structural properties of PGCMs are determined. n-link PGCM has $(n - 1)$ revolute joints and $n - 1 - F$ geared and cam joints. These structural properties are highly important for developing methods for systematic mechanism enumeration. The flow chart for the structure synthesis of PGCMs is shown in Fig. 16. The concept of spanning trees is used to define an algorithm for enumerating PGCM graphs. The 5-vertex spanning trees are listed in Table 3. There are only four spanning trees. Table 4 displays the graphs of the four distinct rooted parent graphs that correspond to the single link assortment array.

As shown in Table 5, the exact findings of the 5-link PGCM graphs have been verified to be 12. The synthesis findings presented here differ from those in reference [24], which has only one geared-cam graph. Because the DOF associated with a cam joint and a gear joint are identical, Hsieh et al. [24] assumed that enumerating cam mechanisms is similar to enumerating geared mechanisms in that they can use a cam joint to replace any gear joint in a geared mechanism without sacrificing mobility. While this is correct, it does not produce a complete set of PGCMs because, unlike the cam pair, the gear pair requires a planet carrier and only revolute joints are permitted. Earlier synthesis techniques made no attempt to include mechanisms with floating output links or prismatic joints. The geared-cam diagrams shown in Table 5 can be transformed into their corresponding functional diagrams. Figure 18 depicts the functional diagram that corresponds to the geared-cam graph shown in Figure 17 (c).

6. Conclusions

A method for creating mechanisms based on kinematic structure is described. A comprehensive database of graphs with five links has been established. The Classification of two-DOF PGCMs with up to seven links is conducted. The exact findings of the 5-link PGCM graphs have been verified to be 12. The reason for the discrepancy between the current results and other methods is explained. The application and significance of this approach in producing a variety of non-uniform motions, developing better alternatives, and creating new designs for variable-speed output mechanisms are demonstrated. A kinematic simulation is used to validate the viability of the new designs.

Authors' contribution

All authors contributed equally to the preparation of this article.

Declaration of competing interest

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